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Pioneer 10/11 Data Analysis of the Plasma Analyzer Experiment

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ABSTRACT

Two major achievements, each of which is unique, were accomplished under this contract. The first was the discovery that the Pioneer 10 plasma analyzer detected the Io plasma torus during the spacecraft's flyby of Jupiter in 1973. Evidence was found of corotating ions which appear to be primarily S^{++} and O^{++} in the Pioneer 10 plasma data as the spacecraft moved inward from 6.9 to 5.4 R_J. The Pioneer 10 plasma profile shows a relative variation with radial distance remarkably similar to the Voyager density profile. Both profiles show a well defined peak falling off steeply toward Jupiter and gradually decreasing away from Jupiter. The Pioneer 10 plasma data are also consistent with a constant temperature for at least 0.5 R_J outside Io's orbit. Our analyses demonstrate that the Pioneer plasma analyzer was surprisingly effective in obtaining information on the heavy ion populations the Jovian magnetosphere. The second major achievement concerned the discovery that interplanetary solar wind plasma shocks can trap energetic particles (cosmic rays) for weeks and out to distances of 17 AU. We found that energetic particles (0.5 MeV to 20 MeV) were confined between two plasma shocks from solar flares (April 15 and 28, 1978) as the shocks propagated outward in the solar system. Shocks associated with both flares are detectable in the Pioneer 10 and Pioneer 11 plasma analyzer data. The shock/flare associations are different from those previously published by others studying the interplanetary events. The apparent ability of a shock whose plasma signature is extremely weak to confine MeV protons in the outer solar system may have significant implications for cosmic ray studies. Contrary to earlier analyses of these data, the results of our analyses also imply significant azimuthal asymmetry in plasma and energetic particle behavior even at distances as far as 16 AU from the sun.

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I. INTRODUCTION

This final report summarizes the work performed at Carmel Research Center under contract NAS2-10925 with NASA Ames Research Center. The work on this contract was performed by Dr. Devrie S. Intriligator, Principal Investigator, and those working under her direction.

Several major scientific discoveries were made under this contract. These discoveries and their significance are discussed below. The importance of these discoveries is so high and the monetary cost of them to NASA is so relatively inexpensive that Carmel Research Center must point out that it is not in the best interests of NASA Ames Research Center nor the overall U.S. NASA space science activity to terminate this contract. Carmel Research Center urges NASA Ames Research Center to continue to support Dr. Intriligator's work on Pioneer 10/11 Data Analysis of the Plasma Experiment.

Dr. Intriligator is the only investigator currently associated with the Pioneer 10/11 plasma experiment who participated in all phases of the instrument design, development, calibration, spacecraft integration, flight, and data analysis. W.D. Miller has worked with Dr. Intriligator on Pioneer data analyses since 1969. G.R. Steele, a Carmel Research Center employee, participated in the instrument design, development, calibration, and spacecraft integration. Carmel Research Center has the capability to continue to provide unique and significant contributions to Pioneer 10/11 data analysis of the plasma experiment. The Carmel Research Center efforts would continue to complement the plasma data analysis efforts carried out by the plasma group at NASA Ames. It is in the best interests of NASA Ames Research Center and NASA in general to continue to support the Carmel Research Center efforts on Pioneer 10/11 data analysis of the plasma experiment.

II. THE DISCOVERY OF THE Io PLASMA TORUS IN PIONEER 10 PLASMA DATA

Publication: "Detection of the Io Torus by Pioneer 10" D.S. Intriligator and W.D. Miller, Geophysical Research Letters, 8, 409-412, 1981 (this paper is reproduced in Appendix I).

This paper presents the discovery that the Pioneer 10 plasma analyzer detected the Io plasma torus during the spacecraft's flyby of Jupiter in 1973. We found evidence of corotating ions in the Pioneer 10 plasma analyzer data as the spacecraft moved inward from 6.9 to 5.4 R_J. We identified these ions as primarily S^{++} and O^{++}. H^+ or He^{++} ions or other light ions were also observed during this time. The Pioneer 10 plasma profile showed a relative variation with radial distance remarkably similar to the Voyager density profile. Both profiles show a well-defined peak falling off steeply toward Jupiter and gradually decreasing away from Jupiter. The Pioneer 10 plasma data are also consistent with a constant temperature plasma for at least 0.5 R_J outside Io's orbit.

This paper is based upon an examination at CRC of the Pioneer 10 plasma observations. The previous study of Pioneer 10 data and the inner Jovian magnetosphere (Frank et al., 1976) did not include the particular telemetered values from which our detections of these ions was inferred. We discovered a number of significant characteristics in the plasma data which are evidence for a variety of plasma phenomena not previously reported in Pioneer data. The basis of our results involves analyzing the data from the outer collectors of the Pioneer 10 plasma analyzer. These collectors view the direction of corotation.

Our analyses demonstrate that the plasma analyzer was actually surprisingly effective in obtaining information on the heavy ion population in the Jovian magnetosphere. We showed that our instrument directly detected a

broad region of significant plasma density surrounding the orbit of Io.

All of the analyses and the interpretation of the data for this study were carried out at CRC by Dr.Intriligator and by those working under her direction.

This paper is reproduced in Appendix I.

III. THE DISCOVERY THAT INTERPLANETARY SOLAR WIND PLASMA SHOCKS CAN TRAP ENERGETIC PARTICLES (COSMIC RAYS) FOR WEEKS AND OUT TO DISTANCES OF 17 AU

Publication: "Plasma Shocks and Energetic Particles in the Outer Solar System: Trapping and Asymmetry Observations from Pioneer 10 and Pioneer 11," D.S. Intriligator and W.D. Miller, Journal of Geophysical Research, in press, 1982 (this paper is reproduced in Appendix II).

We found that energetic particles (0.5 MeV to 20 MeV) were confined between two plasma shocks from solar flares (April 15 and 28, 1978) as the shocks propagated outward in the solar system. This is the first observation of plasma shocks confining cosmic-ray energy particles. These results are important for understanding the modulation of cosmic rays and may also be important for understanding the basic physics involved in plasma shocks trapping and perhaps accelerating energetic particles. The trapped particles may have been accelerated by the shocks, or they may have been ejected by the flares, or they may have been ambient cosmic rays. It is likely that all three sources contributed.

Our results indicate that the propagation of energetic particles and their associated cosmic ray modulation effects may be different from those previously assumed.

Our results are based on our analyses of Pioneer 10 and 11 plasma data and energetic particle data. The radial separation between the locations of the two spacecraft was important for this analysis.

Our results suggest that the continued tracking of Pioneer 10 and 11, as they leave the solar system in opposite directions, is a very high priority since these data are unique and may lead to future discoveries as important as or even more important than those discussed in our paper.

All of the analyses and interpretation of the data for this study were carried out at CRC by Dr. Intriligator and by those working under her direction.

This paper is reproduced in Appendix II.

IV. THE DISCOVERY OF NON-SYMMETRIC PROPAGATION TO THE OUTER SOLAR SYSTEM OF SOLAR WIND PLASMA AND ENERGETIC PARTICLES

Publication: "Plasma Shocks and Energetic Particles in the Outer Solar System: Trapping and Asymmetry Observations from Pioneer 10 and Pioneer 11," D.S. Intriligator and W.D. Miller, Journal of Geophysical Research, in press, 1982 (this paper is reproduced in Appendix II).

We have discovered the first examples of asymmetric propagation of solar wind plasma and energetic particles to the outer solar system. Moreover, contrary to earlier analyses by others of the Pioneer 10 and 11 events associated with the April 15 and 28, 1978 solar flares, the results of our analyses imply significant longitudinal asymmetry in plasma and energetic particle behavior even at distances as far as 16 AU from the sun. Our analysis leads to a clarification of the effects of the shocks including those associated with cosmic ray modulation.

We discovered that the observed Pioneer 10 and 11 shocks show a strong azimuthal asymmetry, each shock being unmistakably evident in the plasma data at one spacecraft and barely detectable in the plasma data at the other spacecraft. The evidence indicates, however, that at large heliocentric distances the very weak shocks still have a strong effect on the MeV protons.

In contrast to the analysis of others, we find from comparison of the energetic particle data at Pioneer 10 and 11 and at IMP that 11-20 MeV protons spread (perhaps latitudinally as well as longitudinally) much more than the 0.5-1.8 MeV protons.

Our results are based on our analyses of Pioneer 10 and 11 plasma data and energetic particle data. The longitudinal separation between the locations of the two spacecraft was essential for this study.

All of the analyses and interpretation of the data for this study were performed at CRC by Dr. Intriligator and by those working under her direction.

This paper is reproduced in Appendix II.

APPENDIX I

GEOPHYSICAL RESEARCH LETTERS, VOL. 8, NO. 4, PAGES 409–412, APRIL 1981

DETECTION OF THE IO PLASMA TORUS BY PIONEER 10

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Abstract. Evidence of corotating ions which appear to be primarily S^{++} and O^{++} has been discovered in data from the Pioneer 10 plasma analyzer, recorded as the spacecraft moved inward from 6.9 to 5.4 R_J during its encounter with Jupiter in 1973. H^+ or He^{++} ions or other light ions are also observed during this time. The Pioneer 10 plasma profile shows a relative variation with radial distance remarkably similar to the Voyager density profile. Both show a well-defined peak falling off steeply toward Jupiter and gradually decreasing away from Jupiter. The Pioneer 10 plasma data are also consistent with a constant temperature plasma for at least 0.5 R_J outside Io's orbit. A radially inward deflection from strict corotation is also evident in our data. Our detailed analysis of the Pioneer 10 plasma instrument's behavior and data in the inner Jovian magnetosphere indicates that the above results are not seriously distorted by radiation background. The previous study of Pioneer 10 data of the inner Jovian magnetosphere (Frank *et al.*, 1976) did not include the particular telemetered values from which our detection of these ions has been inferred.

Introduction

We have recently re-examined the data recorded by the Pioneer 10 plasma analyzers in the inner magnetosphere of Jupiter, and we have discovered a number of significant characteristics which are evidence for a variety of plasma phenomena not reported to data. This note will concentrate on the most spectacular of these new Jovian plasma results, the *in-situ* detection of the Io plasma torus in December 1973. The basis of these results involves analyzing the data from the outer collectors of the plasma analyzer. These collectors view the direction of corotation.

The fact that the Jovian system is variable has been well established on the basis of remote observations of radio, optical and ultra-violet emissions from the inner magnetosphere and Io torus region. However, the only spacecraft to traverse the torus were Pioneer 10 and Voyager 1. Comparison of the Pioneer and Voyager *in-situ* observations can provide very significant insights since the Voyager observations in 1979 were obtained during a period of apparently more activity in the inner magnetosphere (perhaps in association with more volcanic activity on Io) than during the time of the 1973 *in-situ* Pioneer 10 observations. The Pioneer observations were also obtained over a wider range of latitudes in the Jovian magnetosphere.

Observations

The first analysis of the Pioneer 10 plasma probe observations near the Io orbit focused attention on the data from the central sun-oriented collector. Here we study the data from the outer collectors (which could sample corotating plasma), and we show that as Pioneer 10 moved inward past the orbit of Io, plasma currents which were far enhanced over any background were alternately detected on the outermost collectors (collectors 1 and 5) of the medium resolution analyzer as the spacecraft rotated. Figure 1 shows the inbound Pioneer 10 trajectory and indicates the fields of view of the five current collectors in the medium resolution detector (Detector B) of the Pioneer 10 Ames Research Center plasma analyzer. As explained in more detail in Frank *et al.*, 1976, the Pioneer 10 plasma analyzer's five current collectors cover an angular range of ±70° from the centerline of the instrument, the centerline being parallel to the spacecraft's axis of rotation. Figure 1 shows how the trajectory on the inbound pass and the orientation of the spacecraft axis toward the earth combined to bring the corotation direction within the field of view of collectors 1 and 5 by the time Pioneer 10 reached the vicinity of Io's orbit. As each half-spacecraft rotation is divided into 256 equal sectors, and only the readings from the sector with the highest single reading are transmitted, the azimuthal direction of the peak of a distribution that is quite deflected from the centerline is determined by the analyzer within about a degree.

Figure 2 shows a sequence of the ion energy per unit charge E/Q spectra that were obtained from the data on collectors 1 and 5 from 2208 UT (GRT — Ground Received Time) to 2330 UT on December 3, 1973. These spectra are similar to those published previously, for example in association with Pioneer 7 observations of the extended geomagnetic tail (Intriligator *et al.*, 1979). The data from 2208 UT, the first data cycle after an hour-long gap, clearly show a discernable spectrum. The enhanced currents shown in Figure 2 are precisely from the direction expected for corotating ions during the period from 2208 UT (GRT) to 2330 UT on December 3, 1973, over a radial range from 6.9 to 5.4 R_J. The energy spectra show a smooth Maxwellian-like distribution suggesting a single dominant ion species with a temperature of dozens of eV, or several hundred thousand degrees K.

Figure 3 shows two composite spectra near 6.1 R_J obtained by combining the spectra recorded at 2246 and 2251 UT. Curve #1 indicates the composite spectrum from collector 1 obtained by combining the spectra obtained at 2246 and 2251 UT shown in Figure 2. Curve #2 is a similar composite from collector 2 obtained at the same time as curve #1. The spectra obtained at the same time on collectors 5 and 4 are very similar to curves #1 and #2, respectively. Curve #2 shows evidence for another particle population. Comparison of curve #2 with curve #1 shows that the spectrum in curve #2 peaks at roughly half the energy associated with the peak in curve #1. Also, as indicated by the difference in the vertical scales for curves #1 and #2, the peak in curve #2 is much less intense than the peak of the spectrum in curve #1. Collectors 2 and 4 are inner collectors much farther from the expected corotation direction (see Figure 1). The difference in the energy associated with the peak current in the two spectra implies that the particles detected on the inner

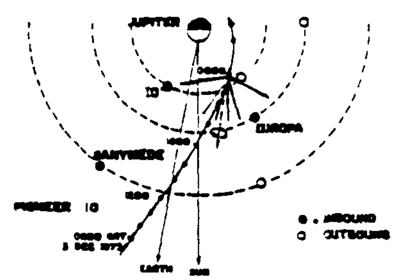

Fig. 1. Projections of the inbound trajectory of Pioneer 10 onto the ecliptic plane during Jupiter encounter in 1973. The projection of the five fans of acceptance of the five current collectors in the medium resolution plasma analyzer (Detector B) is shown. It is clear from this figure that the corotation direction is within the field of view of the outer collectors (collectors 1 and 5) by the time Pioneer 10 reached the orbit of Io inbound.

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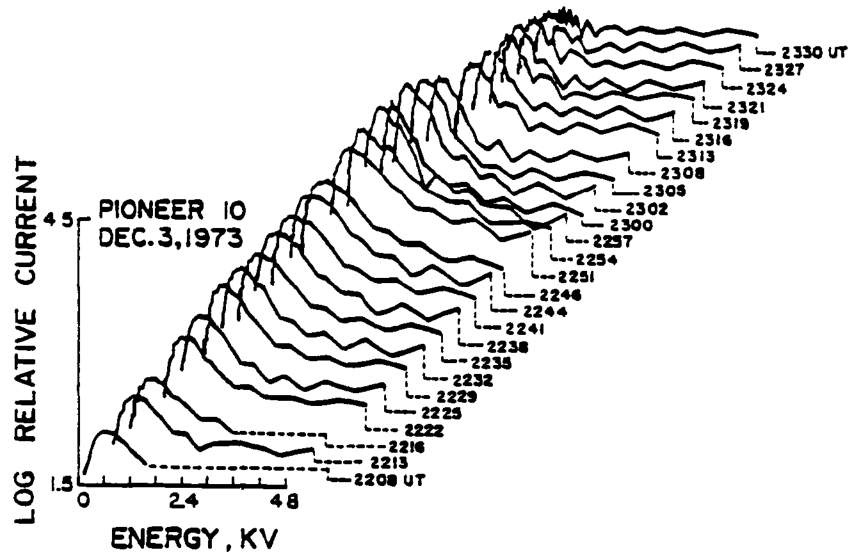

Fig. 2. Ion energy per unit charge (E/Q) spectra measured at Pioneer 10 in the vicinity of Io during the spacecraft's inbound trajectory on December 3, 1973. These spectra were measured on the outer collectors (collectors 1 and 5). These spectra are clear evidence for at least one particle population in this region.

collectors are not merely the outer fringe of the distribution detected on collectors 1 and 5, but a different population — different in mass, charge, temperature, or speed. It appears likely that this distribution is moving in approximately the same direction, but has a lower density than the main population seen on the outer collectors. Thus the main part of this second population probably impinges on collectors 1 and 5 but its signature is buried in the more intense current associated with the first population, and only the outer fringes of the second population appear on collectors 2 and 4. As discussed in the following section, we suggest that the spectrum in curve #1 is due to corotating S^{++} and the spectrum in curve #2 is due to corotating O^{++}.

A close examination of the data provides some indications of additional ion detections. The upper edge of a sufficiently warm distribution of light ions would be above the instrument's energy threshold. There appears to be evidence in a few channels at the lowest energies of a few spectra for the intermittent presence of corotating hydrogen or helium ions or other light ions in the vicinity of the Io torus (e.g. at 5.4, 5.9, and 6.8 R_J). Similarly, some other ion spectra show high energy shoulders or peaks which suggest the presence of some corotating ion or ions with higher E/Q ratios than S^{++}. Finally, there are occasional hints in some spectra of a high energy tail extending to at least 4800 V the upper limit of the instrument's energy scans. This tail could represent either a low density of even heavier ions or a tenuous hot population of one or more of the ions which we observe in the colder, higher density peaks (shown in the figures above). These more subtle detections appear in several spectra implying that they are not merely the result of random fluctuations in the intensities of the more obvious ions.

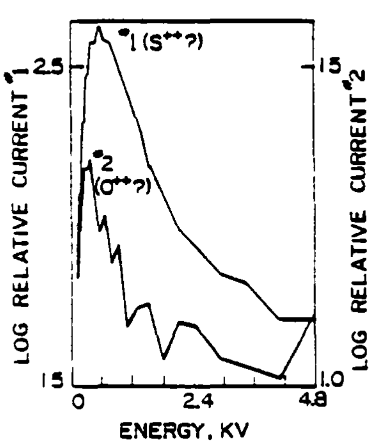

Fig. 3. Ion E/Q spectra obtained near 6.1R_J on December 3, 1973. Curve #1 shows the composite spectrum obtained from collector 1 (an outer collector) by combining the spectra obtained at 2246 and 2251 UT shown in Figure 2. Curve #2 shows the composite spectrum obtained at the same time from collector 2 (an inner collector), with an acceptance fan much farther from the expected corotation direction (see Figure 1). (The spectra obtained at the same time on collectors 6 (outer) and 4 (inner) are very similar to curves #1 and #2, respectively.) A comparison of the spectra in curves #1 and #2 indicates that the spectrum (curve #1) obtained on the outer collector is more intense and peaks at approximately twice the energy of the spectrum (curve #2) obtained on the inner collector. It appears likely that the more intense spectrum (curve #1) is associated with S^{++} and the other spectrum (curve #2) with O^{++} (see Discussion in text).

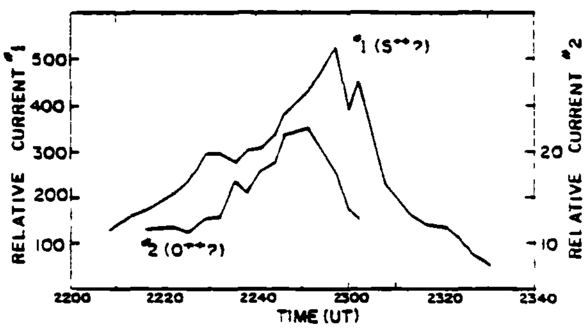

Fig. 4. Radial profiles of the peak ion currents associated with the ion spectra in the vicinity of Io during the Pioneer 10 passage in 1973. These peak ions currents provide a rough estimate of the relative variations of the associated ion densities. Curve #1 therefore provides a rough estimate of the relative ion density measured on collector 1 which may be associated with $M/Q = 16$ and, similarly, curve #2 provides a rough indication of the relative ion density measured on collector 2 which may be associated with $M/Q = 8$. Curves #1 and #2 have linear scales.

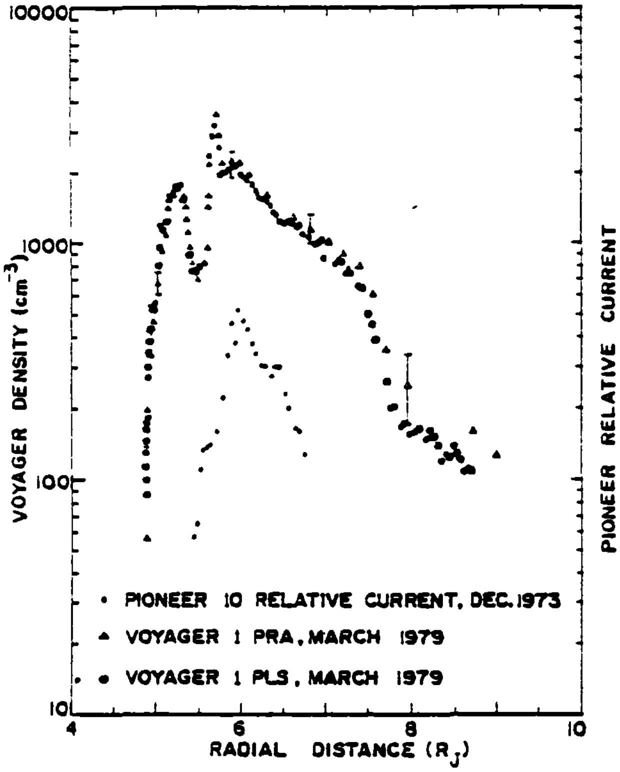

Fig. 5 Relative comparison (on a logarithmic scale) between the Pioneer 10 and Voyager 1 density results (Bagenal and Sullivan, 1981). The Pioneer 10 data are the peak currents shown in curve #1 in Figure 4 The PLS points show the derived ion charge density and the PRA data show the electron density. For clarity we have chosen to vertically separate the Pioneer 10 points from the Voyager points. The exact density values have not yet been determined.

In Figure 4 curves #1 and #2 show the peak current as a function of time of the two particle populations, collector 1 (S^{++}?) and collector 2 (O^{++}?), respectively. These estimates are based on the peak current in each energy cycle when each population is detected unambiguously. These peak currents provide a measure of the relative variations in ion density as a function of time. A comparison of Figures 2 and curve #1 in Figure 4, shows the qualitative effectiveness of this method of obtaining relative ion density estimates.

In Figure 5, we compare the Pioneer 10 peak currents shown in curve #1 in Figure 4, with the Voyager densities derived from the PRA and PLS instruments (Bagenal and Sullivan, 1981) where the PRA densities are electron densities and the PLS densities are their revised ion densities. Figure 5 shows a remarkable resemblance between the Pioneer 10 and the Voyager profiles, with a well-defined peak falling off steeply with decreasing radial distance inside of $\sim 5.7\ R_J$ and dropping off gradually with increasing radial distance outward from this peak. With respect to more quantitative comparisons, we must caution that we do not yet know the exact normalization of the Pioneer 10 data. Since the shape similarity is so great we chose not to draw them superimposed in Figure 5.

Discussion

A. Ion Identification

The energy of the peak currents in these spectra is near the sum of the bulk kinetic energy and the mean thermal energy, so assuming corotation, the spectra in curves #1 and #2 of Figure 3 are consistent with E/Q ratios of 16 and 8, respectively The plasma analyzer separates particles only by energy-to-charge ratios (E/Q), so that it is not possible to separate particles with the same mass-charge ratio and the same speed, such as corotating S^{++} and O^{+} Furthermore, the instrument's ability to separate different ion populations closely spaced in E/Q is limited by a combination of instrument resolution, the temperatures of the populations, and the relative abundances of the populations. In view of the Voyager UV reports (Broadfoot *et al.*, 1979; Sandel *et al.*, 1979) of the Io torus, the plausible identifications are S^{++} and O^{+} for E/Q = 16 and O^{++} for E/Q = 8. The lower apparent density of O^{++} relative to S^{++} or O^{+} is consistent with the Voyager (Broadfoot *et al.*, 1979 and Sandel *et al.*, 1979) and ground-based (Brown, 1976, 1978) estimates of the temperature of the Io torus combined with the high (35 eV) ionization energy needed to convert O^{+} to O^{++} (Leighton, 1959).

It is possible, of course, that these peaks represent higher ionization states of heavier elements or molecules. Neither our spectra nor the available Voyager data provide a basis for inferring that large quantities of elements heavier than oxygen and sulfur are present, and the available UV, ion, and electron spectra do not indicate the solar corona-like conditions that would be needed to produce very high states of ionization. Thus it is possible to restrict consideration to a small range of ion species. The following considerations suggest that S^{++} is the dominant ion in these observations.

In polar velocity space coordinates (the natural system for our instrument, which measures flux as a function of energy and two angles) a convected Maxwellian distribution is described by

$$B(v,p,a) = N\left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\frac{m}{2kT}[v^2 - 2sv\cos(a + a_0)\cos(p + p_0) + s^2]} v^2 \cos a \, dv \, dp \, da$$

where B(v,p,a) is the differential flux as a function of particle speed v, and the azimuthal (a) and polar (p) angles of particle motion. Here s is the speed, and a_0, p_0 the direction angles of convection. Evaluating this function gives the width of the distribution at any value below the maximum, in electron volts for the width in energy or in degrees for the angular width. These widths vary inversely with the mass of the particles, and the angular widths also decrease with increasing convection speed. However, as inspection of the formula shows, the angular width does not depend on charge. Therefore, O^{+} and O^{++} distributions of similar temperatures and flow directions would have similar angular extents, whereas an S^{++} distribution under the same conditions would be only about half as wide, measuring the width at, for example, 0.5 of the maximum. If we consider the actual widths of an S distribution and an O distribution at a temperature of 2×10^{4} K, traveling at 57 km/sec (the speed of corotating ions near Io s L-shell near the magnetic equator relative to the tangential component of the spacecraft velocity) we find widths of 8° and 16°, respectively. Considering that the corotational direction is 12° from the outer edge of the field of view (FOV) and that the outermost detectors extend inward 7 5° from the outer edge of the FOV, it is clear that neither species in any charge state should have been detectable on an inner collector if the motion were strictly corotational. The boundary between the fields of view of the outermost collectors (collectors 1 and 5) and the inner collectors (collectors 2 and 4) for the distribution parameters given above is about 5 standard deviations from the center of a strictly corotating oxygen distribution and 10 standard deviations from the center of a strictly corotating sulfur distribution.

As described above, the actual distribution of the heavy ions is observed only on the outermost collectors, while the lighter ions are observed on the inner collectors. An approximate calculation of possible distributions indicates that, assuming masses of 32 and 16, the observed results can be produced by a ratio of light ions to heavy ones of 2.1, and deflection from corotation of 19° if both species have the same flow direction. Alternatively a density ratio of 1.1, and a deflection from corotation of 22.5° could produce these results. Thus, the available information does not give a unique determination of the density ratio and deflec-

tion, but does indicate that plausible values are consistent with the data.

Our analyses indicate that the departure from corotation results primarily from a radially inward component of motion. The polar component is very slight.

Summarizing the species identification considerations, while the ions with M/Q = 16 could be either S^{++} or O^{+}, the difference in width of the two particle distributions detected indicates that the ions on the outer collectors are genuinely heavier than the ones with M/Q = 8 on the inner collectors. Thus, if the ions on the inner collectors are O^{++}, the ones on the outer collectors are predominately S^{++}. Presumably some O^{+} is present, as implied by the O^{++} ions.

We also note that the region of highest O^{++} density coincides with the region of highest S^{++} density, and both are near the time of crossing of the Io L-shell as calculated from the D3 model of the Jovian magnetosphere (Smith *et al.*, 1975; Kivelson and Winge, 1976).

While we have not presented in detail our light ion detections which might be H^{+} or He^{++} or other ions, we note that they are present intermittently through the Io torus and do not strongly suggest emission from Io.

As illustrated in Figure 5, the radial profile of the estimated relative ion density from our Pioneer 10 plasma analyzer corresponds qualitatively with the densities from the Voyager results (Warwick *et al.*, 1979, Bagenal and Sullivan, 1981). Also, as illustrated in Figure 2 the Pioneer 10 ion spectra appear to be consistent with a relatively constant ion temperature through much of the outer torus at least from ~2222 UT (~6.6 R_J) to ~2251 UT (~6.1 R_J). The Voyager plasma experimenters (Bagenal and Sullivan, 1981) have reported a constant temperature in the outer torus.

B. Instrumental Effects

We have recently analyzed the instrument behavior in detail by careful comparison of the ion data obtained under the most intense radiation (summarized in plate 1 of Frank *et al.*, 1976), the simultaneous electron data (unpublished to date), and the manufacturer's circuit diagrams (also unpublished), so it is now possible to determine that the instrument was not severely affected by radiation in the Io torus.

The peak currents of our spectra detected in the Io torus are some 50 times the apparent background in the Io torus. They are, at least, five times the highest reading from the time of most intense radiation. Also, they are much larger than the currents detected near the orbit of Io on the outbound trajectory, when corotating ions are not in the field of view of the instrument. Currents in these spectra are highly dependent on the energy which the instrument is set to accept, as shown in Figures 2 and 3. This could only occur if a true plasma distribution were entering the instrument aperture. This is unlike the unquestionable radiation effects closer to Jupiter. Therefore, all of our analysis of the Pioneer data and instrumental effects, particularly in light of the subsequent observations of the inner Jovian magnetosphere (Kupo *et al.*, Broadfoot *et al.*, 1979, Bagenal and Sullivan, 1981) leave no doubt that the Pioneer 10 plasma analyzer detected genuine corotating ions.

Frank *et al.*, 1976 focused attention on the data from the center collector (collector 3). We see some evidence of light ions at the lowest energies on collector 3, but all the more obvious heavy ion detections appear on collectors 1,2,4, and 5, as illustrated in Figures 2 and 3. The ion currents we are analyzing are more than five times larger than the highest reading from the time of most intense radiation which was the time interval analyzed by Frank *et al.*

Conclusions

The Pioneer 10 observations presented above demonstrate that the instrumentation was actually surprisingly effective in obtaining information on the heavy ion population in the Jovian magnetosphere. We have shown that the Pioneer 10 plasma analyzer directly detected a broad region of significant plasma density surrounding the orbit of Io. Our analyses indicate that two corotating ion populations are clearly detected over a broad interval. These observations are consistent with identification as S^{++} and O^{++}. Our analyses also imply a radially inward deflection from strict corotation of these ions. We have found evidence of a relatively constant temperature of the ions between ~6.1 R_J and ~6.6 R_J. We have also found intermittent evidence of corotating H^{+} or He^{++} or other light ions.

The 1973 Pioneer 10 ion observations presented above have numerous qualitative similarities to the Voyager observations in 1979. The shapes of the radial profiles are similar, as shown in Figure 5. The way they both show a rapid decrease toward Jupiter and a slower decrease away from Jupiter suggests that such a density profile may be a persistent feature of Io's plasma torus. However, the Voyager peak is at ~5.7 R_J and the Pioneer 10 peak is at ~6 R_J (2257 UT). The Pioneer 10 and Voyager observations both indicate that the temperature was approximately constant over a wide radial distance.

More quantitative analyses of the Pioneer 10 observations will be published in the future. Quantitative comparisons with the Voyager data should help us understand the differences between conditions in December, 1973 and March, 1979 and may provide increased insight into the large temporal variability (Mekler and Eviatar, 1980) of the plasma content of the Io torus.

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APPENDIX II

PLASMA SHOCKS AND ENERGETIC PARTICLES IN THE OUTER SOLAR SYSTEM - TRAPPING AND ASYMMETRY
Observations from Pioneers 10 and 11

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ABSTRACT

Energetic protons (0.5-20 MeV) appear to be trapped between a pair of shocks associated with the major solar flares of April 15 and April 28, 1978. Prolonged trapping (for a period of weeks) is implied by the large count rate enhancement and the large range of radial distances and longitudinal angles over which the trapping is observed. Shocks associated with both flares are detectable in the Pioneer 10 and Pioneer 11 plasma analyzer data. These shock/flare associations are different from those previously published by others studying the interplanetary events. The evidence for trapping has not been recognized heretofore most likely because of the unobservability of the April 15 flare (located $\sim 150^{\circ}$ E of the Sun-earth line) and of the faintness of the signature in the plasma data of one shock in each pair. The apparent ability of a shock whose plasma signature is extremely weak to confine MeV protons in the outer solar system may have significant implications for cosmic ray studies. Contrary to earlier analyses of these data, the results of our analyses also imply significant azimuthal asymmetry in plasma and energetic particle behavior even at distances as far as 16 AU from the sun. The combination of these observations provides evidence for unexpectedly complex interactions in the outer solar system between energetic particles and solar wind plasma.

INTRODUCTION

A very large solar flare (importance 3B) began at 1304 UT on April 28, 1978 in McMath Region 15266 and continued for more than nine hours. Disturbances in solar wind and cosmic ray behavior which were apparently associated with that event were observed at the earth, at Pioneer 11, and at Pioneer 10 (Pyle, et al., 1979; Van Allen 1979). These previous studies inferred from these observations a high degree of cylindrical symmetry in plasma and energetic particle behavior. Pyle, et al., also noted evidence for a large flare on the unobservable hemisphere of the sun on approximately April 15.

Previous studies have shown (Intriligator 1977, 1980) that the shocks from large flares can propagate with nearly constant speed over large radial distances. In the process of our studying Pioneer 10 and 11 plasma analyzer data to determine the apparent propagation speeds of interplanetary shocks in 1978 we discovered evidence of a previously unrecognized forward shock in each data set, a possible reverse shock in the Pioneer 10 data, and a firm association of the large shock on May 27 at Pioneer 10 with the April 15 flare. When we plotted the shocks identified in the plasma data on a figure from Pyle, et al., we found the apparent precise correspondence of each shock with a significant change in the energetic proton count rates at Pioneer 10 and 11. As described below we have concluded that the energetic particle changes indicate that large numbers of particles in the energy range of 0.5-1.8 MeV and 11-20 MeV were trapped between the forward shocks. If this is the case, the observed characteristics of these particles discussed by Pyle, et al., may be due partly to the trapping process, instead of or in addition to the acceleration at the shocks. A careful examination of these observations (see Figure 8 below) also suggests that the azimuthal symmetry of the

energetic proton behavior implied by the analyses of Pyle, et al., and as discussed by Van Allen may have been overstated. However, our analysis actually leads to a clarification of the effects of shocks including those associated with cosmic ray modulation. The increased insight available from careful examination of the detailed plasma analyzer data suggests that further knowledge might be gained by a more comprehensive study involving higher time resolution particle and field data.

The organization of this paper is as follows: In the Observations section first we present the specific features in the Pioneer 10 and 11 plasma data during this period that are relevant for this study. Then we present the available higher time resolution plasma parameters for each of the shocks and present some calculated characteristics of the shocks. Then we show a comparison of the Pioneer 10 and 11 solar wind speed with the energetic particle data. In the Discussion section we first describe our associations of the observed interplanetary shocks with specific solar flare events. In this connection we present some IMP energetic particle measurements that contribute to our identification of the specific solar flare events. Next we discuss the evidence for energetic particle confinement between the interplanetary shocks. Finally, we discuss the longitudinal characteristics of the propagation to extended heliocentric distances of the plasma and energetic particles associated with these events and the evidence for azimuthal asymmetry.

OBSERVATIONS

Figure 1, adapted from Van Allen, shows the geometric relations of the spacecraft and flares in early 1978. As indicated in Figure 1, the earth and Pioneer 10 were about 170^{o} apart in ecliptic longitude with Pioneer 11 about halfway between them. We are primarily studying the effects of the April 15 and 28 flares. The April 28 flare had importance 3B. Since the April 29 flare was a 2B flare, the April 28 flare most likely made the major contribution to the interplanetary disturbance. Both the April 28 and 29 flares occurred in Region 15266. Extrapolation suggests that the flare of April 15 also probably occurred in Region 15266 which was not on the visible hemisphere at that time.

Figure 2 shows a detailed plot of Pioneer 10 speed and density data. In addition to the first large speed and density jump, there are smaller abrupt speed rises which appear to be, respectively, a possible reverse shock and a forward shock, based on the simultaneous density changes recorded. The identification of the second shock as a reverse shock is tentative being based upon the apparent density decrease in the NASA Ames least squares plasma parameters. Figure 3 is a similar plot for Pioneer 11. It shows a small shock on May 8 (Day 128) preceding the large shock on May 11 (Day 131).

Figures 4 through 7 present the available higher time resolution plasma data associated with the Pioneer 10 and 11 shocks shown in Figures 2 and 3. As indicated in Figure 2, the large increase in solar wind speed on May 27 (Day 147) occurred during a data gap so that for this one event the higher time resolution plasma data are not available. However, there is no doubt from the plasma data shown in Figure 2 that a significant increase in solar wind speed and density occurred during this data gap. As discussed below, the uncertainty of when in the data gap the change in the plasma parameters

occurred does not affect any of the conclusions of this study.

Figure 4 shows the higher time resolution data for the next Pioneer 10 shock. These data from June 1 (Day 152) indicate that following a data gap the solar wind speed increases quite sharply from $\sim$480 km/sec to $\sim$ 520 km/sec and the density decreases by about a factor of two. We have, therefore, identified this event as a reverse shock.

Figure 5 shows the higher time resolution data for the third Pioneer 10 shock. This forward shock, which occurs on June 5 (Day 156), is characterized by a sharp increase in speed and a simultaneous density increase.

The next two figures present the Pioneer 11 higher time resolution data associated with the two shocks denoted in Figure 3. Figure 6 shows the forward shock observed on May 8 (Day 128). This shock is characterized by a sharp increase in speed and a small density increase.

Figure 7 shows the higher time resolution plasma parameters observed on May 11 (Day 131). The large sharp jump in speed and the pronounced density increase clearly denote the passage of a forward shock.

Table I summarizes the characteristics of these shocks. The average transit speed of the shock, in km/sec, from the sun to the spacecraft or the earth is shown in the column $V_{s \text{ to } s/c}$. The local speed of the shock, in km/sec, is indicated in the column $V_{shock}\langle V,N\rangle$ (Intriligator, 1980).

The local shock speed was obtained by using the flux conservation equation:

$$V_{SHOCK}\ \langle V,N\rangle = \frac{V_2 N_{p_2} - V_1 N_{p_1}}{N_{p_2} - N_{p_1}}$$

where V_1 and V_2 are, respectively, the preshock and postshock plasma speeds; and N_{p_1} and N_{p_2} are, respectively, preshock and postshock proton number

densities. In the case of the first Pioneer 10 shock, which occurred during a data gap, the plasma parameters measured before the gap and after the gap were used in this calculation. For the remaining shocks representative preshock and postshock values of the plasma parameters were employed.

Figure 8 is a comparison of the Pioneer 10 and 11 solar wind speeds and the energetic particle data. The energetic particle data are from Pyle, et al. Figure 8 shows the times of the shocks in each panel, indicating the apparent coincidence of the rise in the energetic particle count rates with the first forward shock in each case, and the fall of the count rate with the second forward shock.

The reader should note that the energetic particle data are plotted on a logarithmic scale. Therefore, for example, while the three orders of magnitude rise (on ~ Day 110) in the counting rate in the upper panel for the 11-20 MeV protons on Pioneer 11 looks larger than the rise of one order of magnitude on ~ Day 128, in absolute terms a rise from .01 to 10 is not as large as a rise from 3 to 30. These numbers apply approximately to the upper Pioneer 11 panel in Figure 8 and the same comment applies to the other panels of energetic particle data. The variations in the 11-20 MeV counting rates in the Pioneer 10 data probably would not have been considered significant if no other information had been available, but the variations in this plot do correspond to the larger variations in the other panels of Pioneer 10 data. For the time interval between the shocks the counting rates associated with the 0.5-1.8 Mev protons is much larger than the counting rate at other times. The Pioneer 10 data also show that coincident with the second shock there is a decrease in the energetic particle count rate.

The times of several solar flares are shown by the small triangles. These flares produced significant enhancements in the IMP energetic particle

data as plotted in the Solar-Geophysical Data for April 1978 (see also Figure 9 below). The dashed lines denote our inferred associations of variations in particle count rates with the solar flares. These associations are based on the correspondence with the changes in the 0.5-1.8 MeV protons where these events are better separated and their interpretation less ambiguous.

We emphasize that these are not the only events which occurred during this time. Figure 8 also shows plasma and energetic particle variations which are associated with other flares, or perhaps some are associated with CIR's in long-lived streams from coronal holes. However, the April flares discussed in Pyle, et al., were the most important flares for a period of more than a month and we are in agreement with them that these flares and the associated plasma and particle disturbances can be usefully studied as a self-contained group of events.

DISCUSSION

Flare/Shock Associations

Our revision of the flare/shock associations of Pyle, et al., and Van Allen is based upon (1) the apparent coincidence of the plasma and energetic particle variations indicating that a major disturbance passed through the solar system and (2) the evidence we have gathered that the April 15 flare was probably of importance 3 and the observation that the April 28 flare was a 3B flare.

Since the April 15 flare is important in our analysis, even though it was not on the visible disk, it is worthwhile to review the information that indicates this flare's existence. First, from early April to late June, 1978, there was only one plage region on the sun which frequently produced major flares. This region was given McMath numbers 15214, 15266, 15314, and 15368 on four successive solar rotations. The Solar-Geophysical Data abbreviated calendar record indicates that this region is known to have produced two 3B flares and three or four 2B flares during this period when it was on the visible hemisphere of the sun. Since evidence exists of a major flare on the invisible hemisphere of the sun when this region is on that hemisphere, there is a strong presumption that the flare would have occurred in this region. The observed flares of April 8, 28, and 29 discussed in this paper all occurred in this region. Furthermore, it is not improbable that such a large, flare-rich region might emit flares on the invisible hemisphere. The rise in energetic particle flux that is observed at the earth in the IMP energetic particle data late on April 16 (see Figure 9) does not correspond with any visible H alpha flare. However, such large rises in count rates at these energies are not known to be caused by anything other than a solar flare. The obvious inference of a major H alpha flare on the invisible hemisphere is

strengthened by the remarkably slow rise and long persistence of the enhancement. Such behavior is characteristic of flares which occur east of the central meridian of the sun since the particles must reach the earth by cross-field diffusion rather than the direct field-aligned streaming possible for particles from western flares. The farther east the flare, the more diffusion is needed, and so the slower the rise and fall and the lower the peak flux. A flare east of the eastern limb would show these characteristics in an even more exaggerated form. Thus the energetic particle record taken alone is strong evidence that a H alpha flare occurred east of the east limb roughly a day before the particles arrived at earth. Region 15266 was about E150° at this time. Both the known high activity of this region and the long persistence of the particle enhancement, indicating an energetic flare that produced many particles, imply that a large flare occurred at this time. We are referring to this flare as the "April 15" flare because the timing of the arrival of particles suggests that the flare most likely occurred sometime in the morning or afternoon of April 15. However, if the flare occurred late on the 14th the conclusions in this paper would not be changed.

The recent publication on "major flares" (Dodson and Hedeman, 1981) indicates an event on the morning of April 15 from 0630 UT to 0703 UT occurring at N14W08 in McMath Region 15235. Their listed information concerning this flare is unusual in that there is no observed H alpha activity associated with the flare yet they list a great deal of intense radio activity. Based on the IMP and Pioneer observations, we would argue that the listed intense radio activity can be associated with a "major flare" - a 3b flare - on the invisible hemisphere of the sun. The flare could easily have lasted longer than the observed radio activity. We conclude that the recorded radio activity is also supporting evidence for the existence of a major flare

(3b) on the invisible hemisphere on April 15.

Figure 8 indicates the shocks in the Pioneer 10 and 11 solar wind plasma data and the simultaneous changes in the energetic particle observations. Table 1 shows agreement ($\pm \sim 150$ km/sec) between the average transit speeds, $V_{s \text{ to } s/c}$, from the sun to Pioneer 10 and 11 for the April 15 flare. Since the April 15 flare did not occur on the visible disk we do not know the exact time of the flare, although on the basis of the Dodson and Hedeman listing we know that the flare most likely occurred before 0630 UT which would yield a transit speed < 639 km/sec. The transit time from the sun to Pioneer 10 and 11 is long enough that in each case the uncertainty about the time of day when this flare occurred does not lead to significant uncertainty in the average transit speed. However, in the case of the earth the average transit speed is highly uncertain (see Table 1) since the distance and times are relatively short. Identification of the Dodson and Hedeman listing as the flare would give good agreement of speeds in this case also.

Another strong piece of evidence supporting our flare/shock associations is that the first shock was strong at Pioneer 10 but weak at Pioneer 11, while the second shock was weak at Pioneer 10 and strong at Pioneer 11. Given the closeness of Pioneer 10 to the ecliptic longitude of the first flare and the closeness of Pioneer 11 to the ecliptic longitude of the second flare, this relation of shock strengths is just what would be expected based on previous experimental and theoretical studies (Dryer, 1975; Intriligator, 1977) of shock strengths as a function of azimuth from the longitude of the flare. The Pioneer 11 plasma observations on May 8 (Figure 6) associated with the first flare, for example, were measured at a longitude considerably east of the flare site. Dryer (1975) indicates that at this relative location the shock would tend to have the appearance of a quasi- parallel shock with the

attendant jagged plasma parameter fluctuations. The Pioneer 11 plasma data in Figure 6 are consistent with this view of the longitudinal evolution of interplanetary shocks.

As discussed in more detail below, during this time there is also no evidence for other solar events of sufficient magnitude to be likely alternative candidates for the sources of the shocks. The details of the plasma and energetic particle variations at Pioneers 10 and 11 for these events do not resemble a CIR from a coronal hole stream.

It appears that we have evidence from 1 to 16 AU for a correspondence between the depth of a Forbush decrease in cosmic ray detectors and the local strength of a shock as measured by plasma (and perhaps also plasma wave) instruments. Examination of Figure 2 from Van Allen (1979), which for completeness we have reproduced here as Figure 10, indicates that Detector C of the University of Iowa cosmic ray instrument on Pioneers 10 and 11 appears to show small Forbush decreases at about Day 128 (May 8) at Pioneer 11 and Day 156 (June 5) at Pioneer 10, corresponding with the times of arrival of the small shocks we discussed above. Pyle, et al., cite a small decrease on April 17 which they tentatively associate with the April 15 flare. Examination of the IMP solar wind data in the Solar-Geophysical Data shows that a small shock passed the earth at the time of a sudden commencement that began a brief, weak magnetic storm (maximum $K_p = 5^-$). Thus we have evidence that these weak shocks propagated from 1 to 16 AU and produced weak modulation effects while the strong shocks which attracted previous attention produced strong modulation. The "ambient" earth-based observations show that this correspondence is not "perfect" at 1 AU but the existence of such correspondences in these data for larger radial distances raises the possibility that the behavior is simpler at larger distances and may clarify

the complexities seen at 1 AU.

Further evidence of the traversal of the shock may be provided by the possible observations of the shock by the Voyager plasma wave instrument (F.L. Scarf, private communication) and plasma science instrument (J. Belcher, H. Bridge, private communication). The Voyager plasma wave instrument (PWS) observed a shock on April 24, 1978 at approximately 1435 UT. This event is shown in Figure 11. The Voyager 1 plasma science (PLS) data show a moderate ($\leq$ 50 km/sec) increase in speed (in the hourly averages) in association with this event. At this time Voyager 1 was at 3.00 AU and its earth-sun-probe angle was 248.8°. Associating this shock with the April 15 flare we obtain an average transit speed ($V_{s\ to\ s/c}$) for the shock of approximately 550 km/sec. This transit speed is intermediate between the corresponding average transit speeds obtained for this event from the Pioneer 10 and Pioneer 11 observations (see Table I). Moreover, this agreement is particularly reasonable given the longitudinal location of Voyager 1 with respect to the flare site and the Pioneer 10 and 11 spacecraft. The plasma wave observations are most likely indicative of a quasi-parallel shock in agreement with our discussion concerning the plasma observations of this event at Pioneer 11.

We conclude that the April 15 and April 28 flares were extremely energetic events with the April 15 flare producing enormous numbers of highly energetic particles. A rough indication of the energies of these events can be inferred by comparing the energetic particle curves for the April 15 and 28 flares in Figure 8 with the particle production of the April 8 flare which was a 2B event. Comparing the particle and plasma data for these events with those, for example, of the August 1972 events suggests that often flares smaller than importance 3 are not as likely to have sufficient power to cause major shocks in the outer solar system. Importance 3 flares are sufficiently

rare that observations of a pair of such flares, within two weeks, followed by the observation of plasma and particle disturbances in the outer solar system generally consistent with the constant speed approximation used successfully elsewhere, provides a strong presumption for associating corresponding events. It is tempting to speculate that had the April 15 flare occurred on the visible hemisphere of the sun, as the April 28 flare did, it would have been classified as of importance 3 and the interplanetary associations might have been deduced immediately. The IMP particle detector record indicates clearly that no major H alpha flares occurred, though several minor flares did, between April 15 and April 28. Coronal holes and their associated high speed streams usually do not produce such disturbances in the inner solar system. Also, the characteristics of corotating interaction regions (CIR's) are quite different from the plasma and energetic particle observations presented in this paper. Therefore, it appears that there are many lines of evidence supporting our flare/shock associations.

PARTICLE CONFINEMENT

Confinement of the energetic particles between the forward shocks is strongly suggested by the manner in which the particle count rates rise with the first forward shock and fall with the second. Currently we do not have access to higher time resolution energetic particle data so that the exact timing of the energetic particle variations cannot be defined in greater detail. However, the coincidence of the shocks and the gross changes in the energetic particle count rate is so evident that the principal aim of future more detailed studies (e.g., employing higher time resolution energetic particle data) is likely to be directed toward studying the structure or mechanism of this event, or comparison with other events.

All of the observations are consistent with a view in which energetic particles from the April 1978 solar flares, as well as particles accelerated at the shocks, were confined between the two shocks, and were compressed as the faster moving second shock was overtaking the first shock. If we consider Figure 8, we see that it must show two groups of particles from each flare - the ones arriving first that propagate freely to the spacecraft and the trapped particles arriving later since they are confined by the interplanetary shocks. The particles that propagate freely to the spacecraft travel with a speed of tens of thousands of kilometers per second, and even allowing for irregular paths in diffusion, arrive at the spacecraft in only a few days. In contrast, the trapped particles must have a bulk motion no faster than the plasma shocks which confine them and which travel at speeds of hundreds of kilometers per second. Thus the trapped particles arrive with the shocks much later than the freely propagating particles. Generally some particles for each flare would be trapped and some would propagate freely.

A schematic depiction of this trapping concept is presented in Figure

12. In this figure the locations of the shocks and the trapped particles are depicted approximately as they would have been on May 8 when the first shock reached Pioneer 11. The shock fronts in the vicinity of Pioneer 10 and 11 have been drawn by using the constant-speed approximation discussed above and connecting the points with arcs of circles. The trapped particles have been depicted extending over this angular range, and slightly beyond, since it appears plausible that the particles could be present over the angular range between the two spacecraft and perhaps outside. The constant-speed approximation indicates that the second shock would overtake the first shock near 9 AU in the ecliptic longitude vicinity of Pioneer 11. This would imply that the appearance of the shocks and particles may be significantly different as they approach Pioneer 10. The reverse shock is not shown in Figure 12 since we do not know where it was formed.

The shape of the shock fronts is likely to have been a little different from the arcs of circles shown in Figure 12 but available observations do not provide enough information for a more realistic portrayal. In particular, the shape of the second shock front, propagating into the ejected gas from the first solar flare and into the shocked ambient solar wind, is difficult to estimate. Table I shows that the constant speed assumption clearly does not hold as well for the second shock as it does for the first - the first shock, of course, propagated into relatively undisturbed solar wind. However, the behavior of the second shock may be comparable to the larger apparent speed variations of the shock associated with the third solar flare of the August 1972 events (Intriligator, 1977), which also propagated into disturbed solar wind conditions. Sufficient numbers of multi-spacecraft observations and hydrodynamic calculations, such as those described in Dryer (1975), should eventually allow more realistic estimates of shock propagation and shock

shapes in the outer solar system.

In the case of the April/May events, it appears possible that some of the observed characteristics of the energetic particles in the vicinity of the shocks might be partially due to the trapping process. Specifically, the absence of dispersion with energy may be understandable in terms of the particle confinement between the shocks. If the particles have been reflected repeatedly between the shocks, rather than propagating freely from the sun, this may account for the lack of dispersion.

An additional line of evidence for particle confinement may be found in comparing the relative magnitudes and durations of the energetic particle enhancement between the two shocks in this event with the magnitude and duration of the enhancements at both Pioneer 10 and 11 associated with the single major shock emanating from the solar flare on September 23, 1978, and perhaps also from the flare of September 27, 1978. Another figure from Pyle, et al., a portion of their Figure 4 which we have reproduced here as Figure 13, indicates that in the case of the September flare the effect at both spacecraft is almost undetectable for 11-20 MeV protons, and the enhancement in 0.5-1.8 MeV protons at Pioneer 10 was strong but brief when the shock passed with a rapid rise and a more or less exponential decline. Thus, the energetic particle observations for these September flare events are unlike the more nearly rectangular profile of the energetic particle enhancement in the same energy range observed between the April shock pair as shown in Figure 8 above. Similarly, the enhancement in this energy range at Pioneer 11, when the shock for the September event reached there in late October, was also much smaller than the energetic particle enhancement between the shocks associated with the April events shown in Figure 8 above.

A recent paper (Webber and Lockwood, 1981) may provide indirect evidence

for the trapping of energetic particles between interplanetary shocks. Webber and Lockwood studied the long-term modulation of cosmic rays with energies greater than 60 MeV, employing Pioneer, Voyager, and IMP data from 1972-1980. They conclude that "the long-term modulation effects are propagated outward radially from the sun with a typical speed of 350-500 km/sec." These authors discuss this outward propagation effect and the fact that it is opposite to a time dependent cosmic ray model (O'Gallagher and Maslyar, 1976) which assumes inward propagation from the extended boundary. Webber and Lockwood conclude that conventional stationary state modulation theories need to be modified. It is tempting to speculate that the solar modulation effects' outward radial propagation at speeds comparable to the solar wind speed is attributable, at least in part, to the confinement of energetic particles between interplanetary shocks.

Two interesting speculations are raised by the considerations of shock propagation. Pioneer 10 is travelling toward the expected tail of the heliosphere and it is possible that another spacecraft at 16 AU moving, for example, toward the heliosphere apex, would not have seen the prolonged modulation observed by Pioneer 10. That is, in the direction away from the apex (toward the tail) the solar wind is expected to remain supersonic and fully ionized to larger distances from the sun than it is in other directions. Thus, a plasma shock front would be able to propagate to larger heliocentric distances in the heliospheric tail direction than in other directions where it would reach the heliosphere boundary sooner. Therefore, the shock would continue to be a barrier to energetic particle propagations longer in this tail direction than in other directions.

A related speculation concerning modulation concerns the properties of the shocks themselves. We noted above that the shocks from the September

flares produced negligible acceleration in the 11-20 MeV protons at Pioneers 10 and 11. Pyle, et al., note that the September flare also produced negligible modulation of cosmic ray particles. In contrast the shocks associated with the April flares had large effects on the 11-20 MeV protons (which presumably included some acceleration), and produced a large modulation effect which Pyle, et al., discuss at length. This raises the question of how the acceleration spectrum of a shock relates to its modulation effect. Based on this evidence, it is tempting to speculate that a shock which accelerates more particles may be a better modulator of particles from other sources. If such a relation exists, it might clarify phenomena observed at many locations in the solar system. However, proving such a relation might involve a related question of considerably more basic physical significance. For a shock to be a persistently effective accelerator or modulator requires it to have some property which is characteristic of the shock itself and not of the plasma through which it propagates. The nature of this property might be simply geometric, perhaps no more than something related to its angular extent; or it might be fluid dynamic, such as the Mach number difference across the shock; it might involve turbulence properties or something as subtle as spectral properties of the plasma waves within the shock. If such effects would be demonstrated and understood, it might be a significant advance in space physics and basic plasma physics. However, at the moment it is not clear how such phenomena could be produced in the laboratory and analyzing such effects in observations of natural phenomena would be very complex.

AZIMUTHAL ASYMMETRY

A careful examination of the data which we will describe in detail below provides a variety of evidence for lack of cylindrical symmetry in particle behavior. These departures from azimuthal symmetry could be the result either of the persistence of the extreme azimuthal asymmetry in the particle flux nearer the sun or they could be the result of solar wind effects. We will first present evidence for initial asymmetries in the particle populations. This evidence appears stronger than the possible effects from the solar wind. Nevertheless, the data are not detailed enough to distinguish clearly between these different possible explanations.

As noted in the Observations, the triangles in the upper part of Figure 8 denote the times of the flares. We have used the dashed lines to connect the flares to their associated energetic particles rises. The Pioneer 10 observations show that the particle fluxes from the April 28 and 29 flares were greater at Pioneer 10 than the fluxes from the April 15 flare. The flux of 0.5-1.8 MeV protons was about ten times higher before the arrival of the particles confined by the shocks, and the flux of 11-20 MeV protons was about twice as high. However, the data in Figure 9 at the earth do not suggest that the particle population produced by the April 28 and 29 flares was notably softer than the particle population from the April 15 flare. In the broad rise associated with the April 15 flare, each particle population reaches a peak value of 10^{-2} of the peak on May 1 from the April 28 and 29 flares. This suggests that the shapes of the particle spectra for these flares were quite similar. The validity of the comparison between the data obtained in the vicinity of the earth and that obtained at Pioneer 10 is apparently confirmed by comparison of these later April flares and interplanetary events with those of the flare of April 8 and its associated observations. The IMP

data confirm that this flare produced a much softer particle spectrum than either of the later flares - the peak flux for 0.16-0.22 MeV particles after April 8 is more than ten times higher than the peak flux in this energy range following the April 15 flare. Since these observations were made under similar conditions, when the spacecraft was inside the earth's magnetosphere, this comparison is important. These observations and other IMP observations of the low and intermediate energy proton data indicate that the data are not seriously compromised by the magnetospheric location. The April 8 flare spectrum decreases much more rapidly with increasing energy than the April 15 spectrum. For the 40-80 MeV protons, the April 8 peak flux is about 10 times lower than the April 15 peak flux. The ratios at intermediate energies have intermediate values. This observed softening of the spectrum for the April 8 flare has its counterpart in the Pioneer observations. Figure 8 shows an unmistakable peak corresponding to the April 8 flare in the 0.5-1.8 MeV data from each spacecraft, but no clear variation in the 11-20 MeV data. The broad peak in the Pioneer 11 data clearly begins several days before the April 8 flare.

Comparison of the particle data discussed above strongly suggests that the 11-20 MeV protons spread out (perhaps latitudinally as well as longitudinally) much more than the 0.5-1.8 MeV protons. This is also suggested by the smoothness of the time profiles of the higher energy protons as compared with the profiles of the low energy protons. Each flare produces a separate peak in the low energy proton data at both Pioneer 10 and 11, while observations from both spacecraft show much smoother variations in the higher energy proton count rates. Thus we see that the spreading process seen at 16 AU appears already well advanced at 7 AU.

Thus it also may be significant that the peak count rates associated with

the April 28 and 29 flares at Pioneer 11 are lower, by a factor of approximately five than the peak count rates for the April 15 flare, reversing the relation seen at Pioneer 10.

A strong departure from azimuthal symmetry for protons at > 80 MeV is indicated by the comparison of the peak in the Pioneer 11 count rate about Day 112 (April 22) in Figure 2 of Van Allen (see Figure 10 in the present text) with the corresponding Pioneer 10 data. No corresponding peak is apparent in the Pioneer 10 data. The peak in the Pioneer 11 energetic proton data occurred at a time consistent with its being associated with the April 15 flare. Moreover, we calculate that Pioneer 11 was about 100^{o} away from field lines connecting to the site of the April 15 flare, while Pioneer 10 was about 200^{o} away. Thus Pioneer 11 was much more favorably located for detecting particles from that flare than was Pioneer 10.

Comparison of the 11-20 MeV panels in Figure 8 above suggests that the spectrum of this event at Pioneer 11 was significantly harder than the spectrum of the corresponding event at Pioneer 10. In addition, the Pioneer 11 spectrum for this event was also much harder than the spectrum detected at both Pioneers in association with the April 28 flare. The contrast is even more extreme when the > 80 MeV data from Van Allen, as discussed above, are included. Rather than increasing symmetry with radial distance as with energy, this result suggests departures from azimuthal symmetry and perhaps even a surprising increased beaming as a function of energy of the high energy particles along the field lines.

Interplanetary acceleration is another possible explanation for some of the phenomena discussed above. The large distances between the spacecraft, both radially and azimuthally, and the absence of out-of-ecliptic observations, raise the possibility that unobserved stream-stream interactions

or some other process which is presently not clearly understood, may have accelerated large numbers of particles from lower energies nearer the sun up to energies in the 0.5-1.8 MeV range or higher. However, the rise in particle count rate at Pioneer 10 between approximately May 15 and May 25 (Day 135 and Day 145), 1978 discussed above, for example, is smoother than the impulsive acceleration usually observed at shocks. The available plasma analyzer data, while covering less than half of each day, nevertheless do not show any strong evidence for additional strong shocks. At the moment we are far from having enough evidence to make any definite claims for the role of interplanetary acceleration in the Pioneer 10 and 11 data at times well before and well after the shocks discussed above. However, the stream-stream interactions that produce known interplanetary acceleration effects tend not to be azimuthally symmetric, so that this alternative mechanism could also prevent the attainment of azimuthal symmetry in energetic particle distributions.

The complexity of behavior thus revealed suggests that if azimuthal symmetry is attained by particles ejected from solar flares, it is highly energy dependent. These results raise the possibility that the 11-20 MeV particles did not reach azimuthal symmetry at 16 AU. Similar characteristics of relative smoothness of the lower and higher energy particles and other evidence of a lack of azimuthal symmetry at 0.5-1.8 MeV are shown in the September-October 1978 data in Figure 4 of Pyle, et al. (see Figure 13 in the present text). This evidence for highly energy-dependent cross-field diffusion of Mev protons over a wide range of radial distances in the outer solar system appears to clarify the highly energy-dependent modulation by the shocks associated with the April flares shown in Figure 2 of Pyle, et al.

The heliospheric tail effect that we speculated on above could be a boundary condition breaking down cylindrical symmetry at sufficiently large

heliocentric distances, even if the symmetry was present closer to the sun. However, examination of Figures 8 and 9 above suggests that the variations of the energetic particles is not entirely independent of flare longitude although considerable spreading evidently occurs.

CONCLUSION

The Pioneer 10 and 11 plasma analyzers observed a pair of shocks from conveniently located solar flares which occurred on April 15 or 16, and on April 28 (and 29), 1978. Comparison of the plasma data with the simultaneous energetic proton data indicates that large numbers of protons having energies between 0.5 and 1.8 MeV, and between 11 and 20 MeV (hence also, presumably, in the intermediate 1.8-11 MeV range) were trapped between these shocks. The trapped particles may have been accelerated by the shocks, or they may have been ejected by the flares, or they may have been ambient cosmic rays. It is likely that all three sources contributed to the final populations.

A recent paper (Webber and Lockwood, 1981) on the long-term modulation of cosmic rays (> 60 MeV) may provide indirect evidence for the trapping of energetic particles between interplanetary shocks. After studying Pioneer, Voyager, and IMP data from 1972-1980 they concluded that solar modulation effects are propagated outward radially from the sun at speeds comparable with the solar wind speed; and consequently, that conventional stationary state modulation theories need to be modified. It is tempting to speculate that their results are attributable, at least in part, to the confinement of energetic particles between interplanetary shocks. Both our results and those of Webber and Lockwood indicate that the propagation of energetic particles and their associated cosmic ray modulation effects may be different from those previously assumed (e.g., Pyle, et al., Van Allen, O'Gallagher and Maslyar, etc.).

This is the first report, to our knowledge, that shocks whose plasma signatures are as faint as the smaller shocks described above can apparently significantly affect MeV protons. Considering that Pioneer 11 was approximately 100° W of the April 15 flare and that Pioneer 10 was about 130°

E and 150° E of the April 28 (and 29) flares, respectively, these observations are direct evidence for shock effects that could produce modulation, "not only around the equatorial zone...but at least to moderately high latitudes" (Pyle, et al.).

The observed shocks show a strong azimuthal asymmetry, each shock being unmistakably evident in the plasma data at one spacecraft and barely detectable in the plasma data at the other spacecraft. The azimuthal variation of shock strength is consistent with studies employing observations obtained closer to sun. It is also consistent with theoretical studies at closer heliocentric distances (e.g., Dryer, 1975). The evidence indicates, however, that at large heliocentric distances the very weak shocks still have a strong effect on the MeV protons.

The azimuthally varying plasma behavior suggests that the azimuthal symmetry which was inferred by Pyle, et al., and Van Allen for the more energetic particles also may not be complete. We have found variations in energetic proton behavior which are consistent with energy-dependent cross-field diffusion or perhaps with some possibly unfamiliar interplanetary acceleration process. Either possibility could lead to azimuthal asymmetries which might actually clarify the observed energy-dependent modulation.

Further insight might be obtained from continued tracking of Pioneer 10 and Pioneer 11 and Voyagers 1 and 2 as they move outward from the sun and as the solar cycle progresses. In particular, Pioneer 10 is the only spacecraft moving toward the heliospheric tail. If the declining phase of the solar cycle produces large flares comparable to the August 1972 events, we shall be able to see what effect they have on the plasmas and energetic particles of the outer solar system.

ACKNOWLEDGEMENT

This paper represents one aspect of research carried out by Carmel Research Center for NASA Ames Research Center under Contract NAS2-10925 and for NASA Headquarters under Contract NASW-3515. The Pioneer 10/11 plasma parameters utilized in this study are based on our analyses of the Experiment Data Record (EDR) and our analyses of the least squares output from the NASA Ames Research Center plasma program. We thank the Ames plasma group for making the least squares data available for us. We are indebted to Dr. F.L. Scarf (TRW) and Drs. J. Belcher and H. Bridge (MIT) for generously providing their Voyager data.

References

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Van Allen, J.A., Galactic Cosmic Ray Intensity to a Heliocentric Distance of 18 AU, Ap.J., 238, 763, 1980.

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TABLE I

Location	Shock	Date	Time, UT	V_s to s/c	$V_{shock}\langle V,N\rangle$	Flare
Pioneer 10	fwd	May 27	0000	678	649	April 15
Pioneer 10	rev?	June 1	0427	-	470	-
Pioneer 10	fwd	June 5	0640	738	579	April 28
Pioneer 11	fwd	May 8	0300	526	492	April 15
Pioneer 11	fwd	May 11	1800	910	766	April 28
Earth	fwd	April 17	2345	600-800	530	April 15
Earth	fwd	April 30	0951	925	576	April 28

FIGURE CAPTIONS

Figure 1. Pioneer 10 and 11 locations and the geometric relations of the spacecraft and flares in early 1978 (adapted from Van Allen, 1979). The principal flares which we consider are the 3B flares on April 15 and 28.

Figure 2. Detailed plot of Pioneer 10 speed and density data. Gaps indicate times of no tracking. The shocks are indicated. The first shock appears to have occurred during a tracking gap.

Figure 3. Detailed plot of Pioneer 11 speed and density data similar to that shown for Pioneer 10 in Figure 2.

Figure 4. Higher time resolution Pioneer 10 plasma data on June 1, 1978. On the basis of the increase in speed and the accompanying density decrease we have tentatively identified this event as a reverse shock.

Figure 5. Higher time resolution Pioneer 10 plasma data on June 5, 1978. On the basis of the sharp increase in speed and a simultaneous density increase this has been identified as a forward shock.

Figure 6. Higher time resolution Pioneer 11 plasma data on May 8, 1978. The sharp increase in speed and the (small) density increase have led us to identify this as a forward shock.

Figure 7. Higher time resolution plasma data on May 11, 1978. On the basis of the large increase in speed and the pronounced density increase we have identified this as a forward shock.

Figure 8. Parallel plots of energetic protons in two energy ranges and the solar wind speed at Pioneers 10 and 11. The shock times are marked in each panel to show the coincidence of the plasma and particle changes. Triangles show the times of the flares which caused the shocks. The black triangles denote flares observed on the visible hemisphere; the white triangle denotes the April 15 flare, which is inferred from the plasma and particle data. Dashed lines show associations between flares and variations in the energetic particle count rates. The variations are both distinct rises and changes in the slope of the count rate. The ordinates for the energetic proton data are logarithmic. The small vertical lines with circles in the two top panels denote the heliocentric distance of the respective spacecraft - the 7 AU location for Pioneer 11 is shown and the 16AU location for Pioneer 10 is shown (the 15.5 AU location for Pioneer 10 is indicated without a label). This figure is adapted from Pyle, et al., but we corrected a two-day offset in the Pioneer 11 data and where available we replaced the quick look solar wind speeds with the speeds from least squares fits to the data.

Figure 9. Energetic particle data from detectors on the IMP spacecraft for the particle variations associated with the flares discussed in the text. These data were replotted on a single vertical scale from plots with varying scales in Solar-Geophysical Data. The

curves are particle count rates for protons in the specified energy ranges in MeV. Note the very prolonged enhancement apparently associated with the April 15 flare. The rises associated with the April 28 and 29 flares are so large that the curves have been labeled again on the right side of the large panel in order to clearly identify the count rates after these flares. The data associated with the April 8 flare are shown in the small panel for comparison (see text).

Figure 10. Figure 2 from Van Allen (1979). Upper panel: daily mean scaled counting rate of Alert neutron monitor (Solar Geophysical Data, 1978); middle panel: five day weighted running mean counting rates of University of Iowa detector C (protons > 80 MeV) on Pioneer 11; lower panel: the same for detector C (protons > 80 MeV) on Pioneer 10. The approximate onset time of the Forbush decrease and the heliocentric radial distance and ecliptic longitude are shown in each case. All ordinates are logarithmic.

Figure 11. Voyager 1 plasma wave observations of the passage of a shock on April 24, 1978 (F.L. Scarf, private communication). We identify these observations with the passage of the shock associated with the April 15 flare.

Figure 12. Schematic depiction of the estimated shock and particle configuration in or near the ecliptic plane about May 8, 1978. The total angular extent of the shocks and trapped particles in the ecliptic plane is not known, nor is the behavior well away

from the ecliptic. As the shock speed varied with ecliptic longitude the shock fronts are drawn as arcs of circles not centered at the sun. Assumptions used in constructing the figure and the limits of the extrapolations are discussed more in the text.

Figure 13. Adapted from Figure 4 of Pyle, et al. The energetic proton observations associated with the September flares are unlike the more nearly rectangular profile of the energetic proton enhancement in the same energy range observed for the April shock pair shown in Figure 8 (see text).

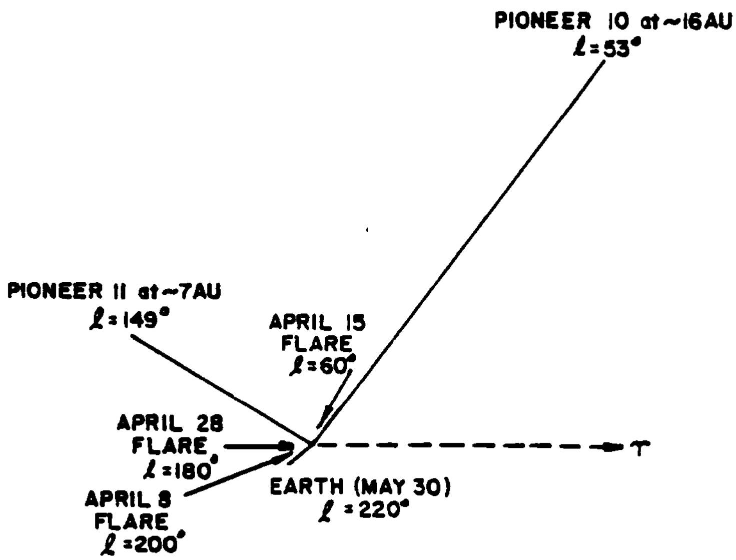
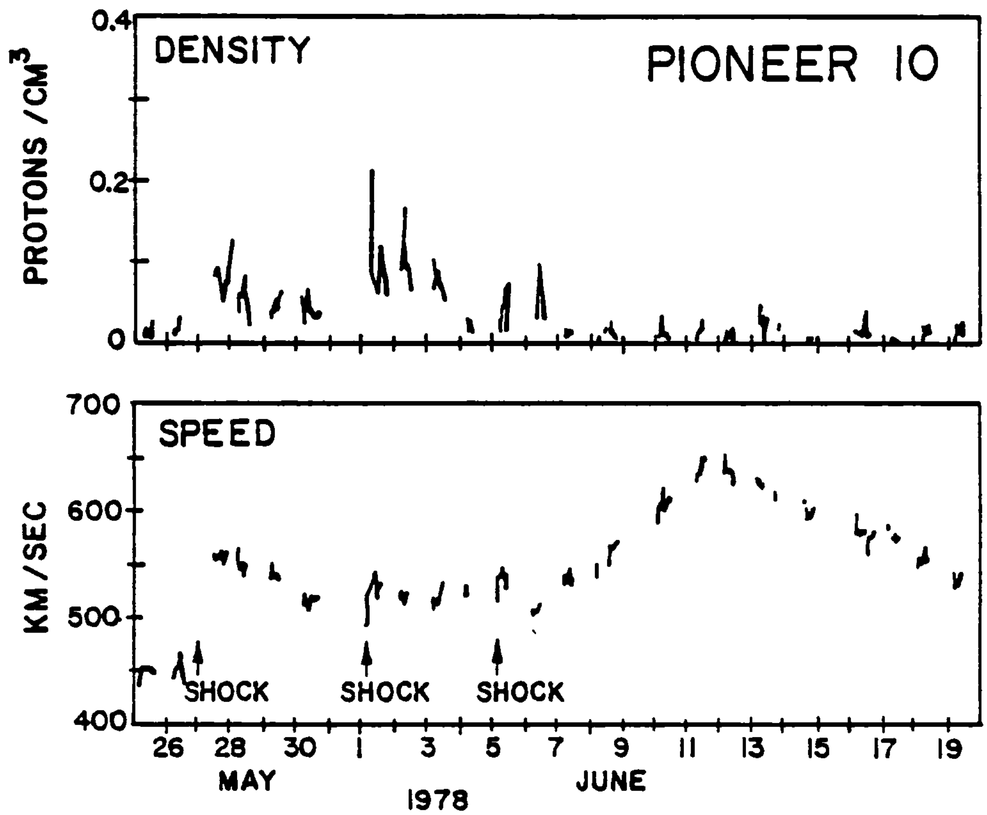
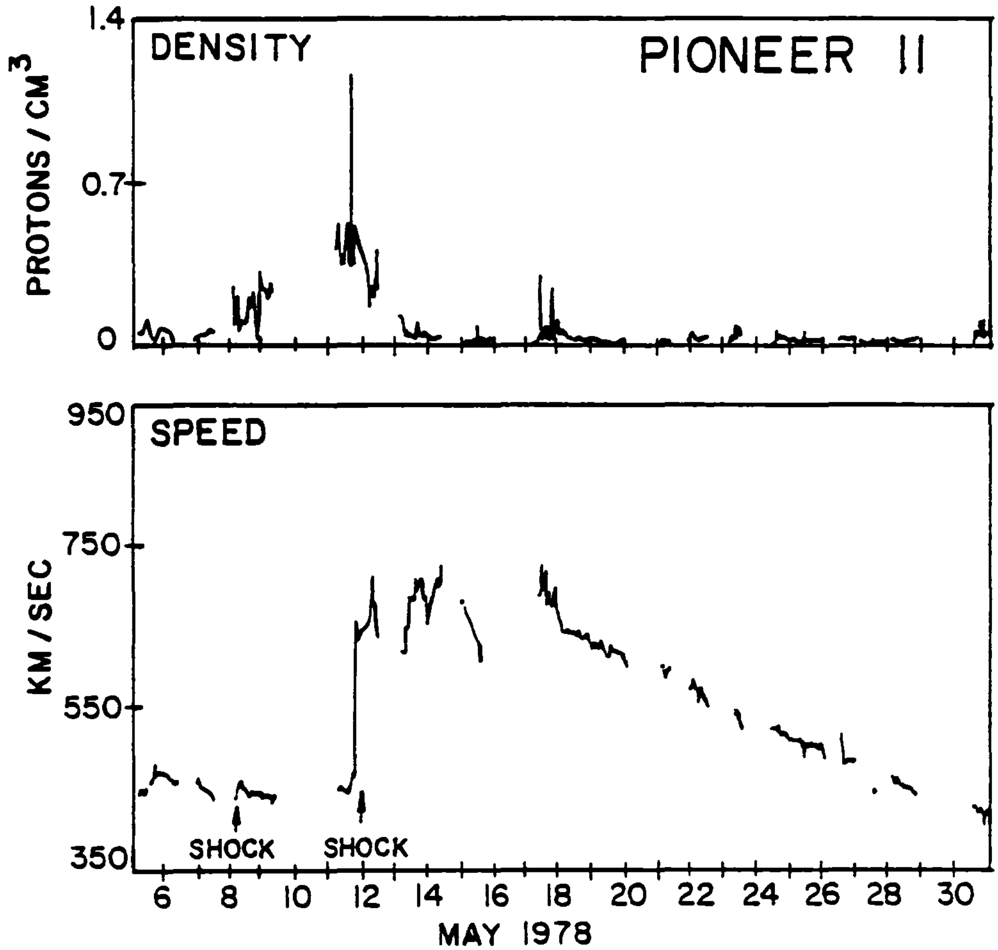

PIONEER 10 at ~16AU
ℓ = 53°
PIONEER 11 at ~7AU
ℓ = 149°
APRIL 15
FLARE
ℓ = 60°
APRIL 28
FLARE
ℓ = 180°
APRIL 8
FLARE
ℓ = 200°
EARTH (MAY 30)
ℓ = 220°
♈

FIGURE 1



DENSITY
PIONEER 10
PROTONS /CM³
0.4
0.2
0
SPEED
KM/SEC
700
600
500
400
SHOCK
SHOCK
SHOCK
26
28
30
1
3
5
7
9
11
13
15
17
19
MAY
1978
JUNE

FIGURE 2



DENSITY
PIONEER 11
PROTONS / CM^3
1.4
0.7
0
SPEED
KM / SEC
950
750
550
350
SHOCK
SHOCK
6
8
10
12
14
16
18
20
22
24
26
28
30
MAY 1978

FIGURE 3

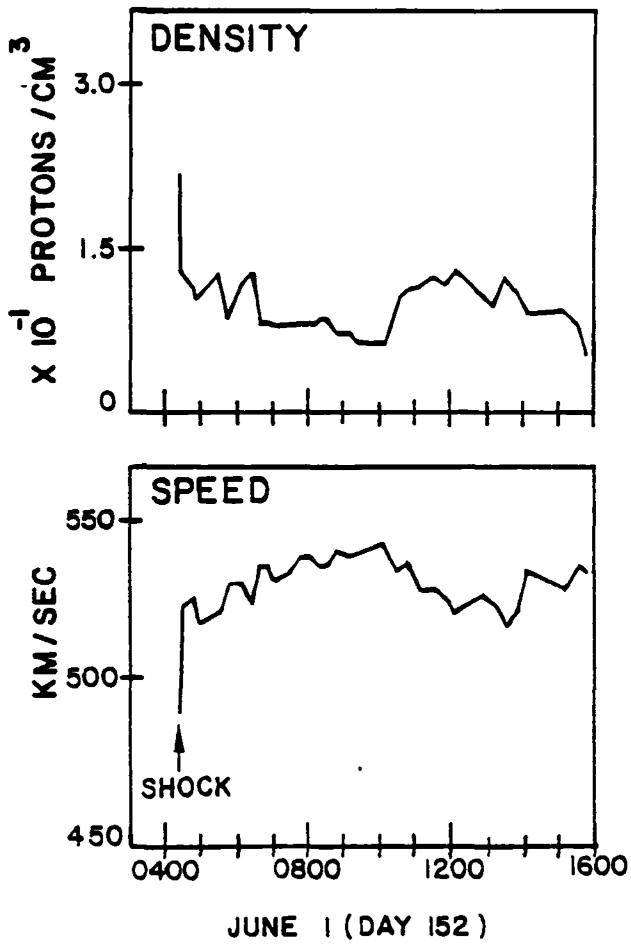
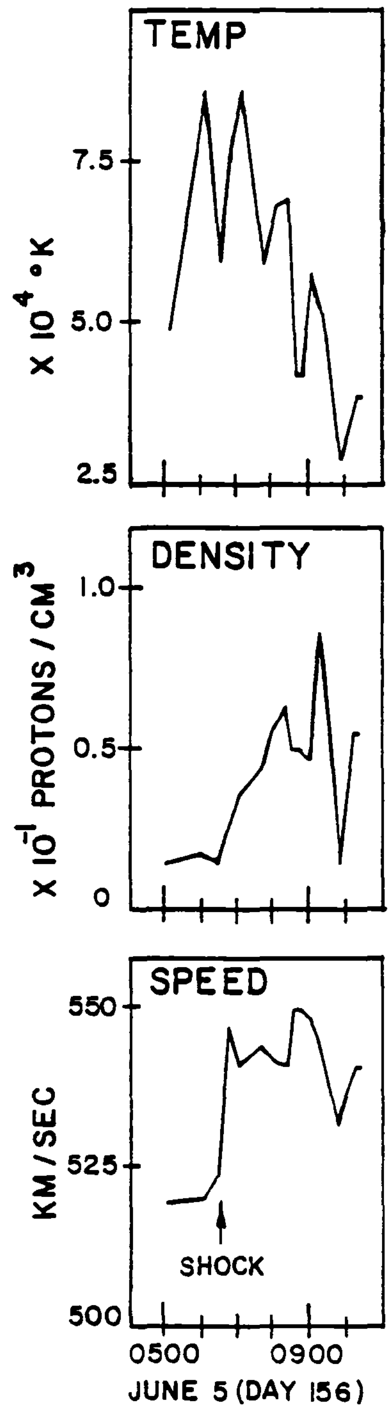

DENSITY
3.0
1.5
0
X 10^{-1} PROTONS / CM^3
SPEED
550
500
450
KM / SEC
SHOCK
0400
0800
1200
1600
JUNE 1 (DAY 152)

FIGURE 4



TEMP
7.5
5.0
2.5
X 10^4 °K
DENSITY
1.0
0.5
0
X 10^-1 PROTONS / CM^3
SPEED
550
525
500
KM / SEC
SHOCK
0500
0900
JUNE 5 (DAY 156)

FIGURE 5

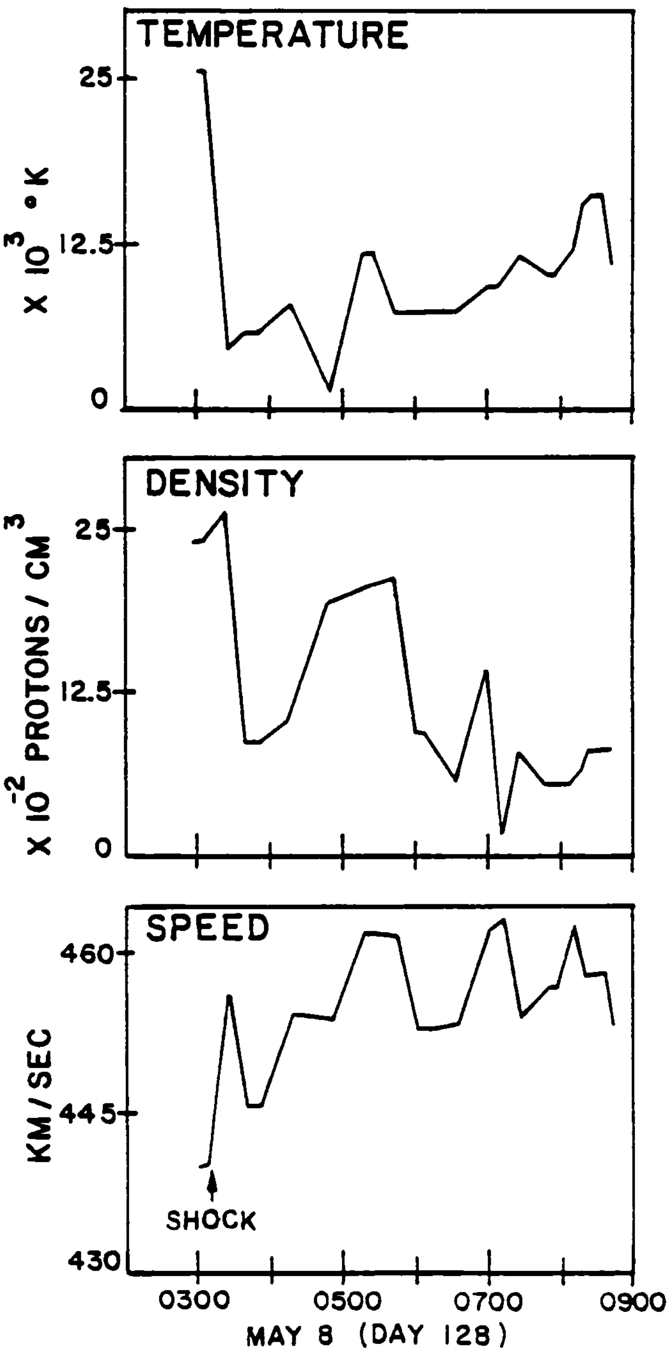
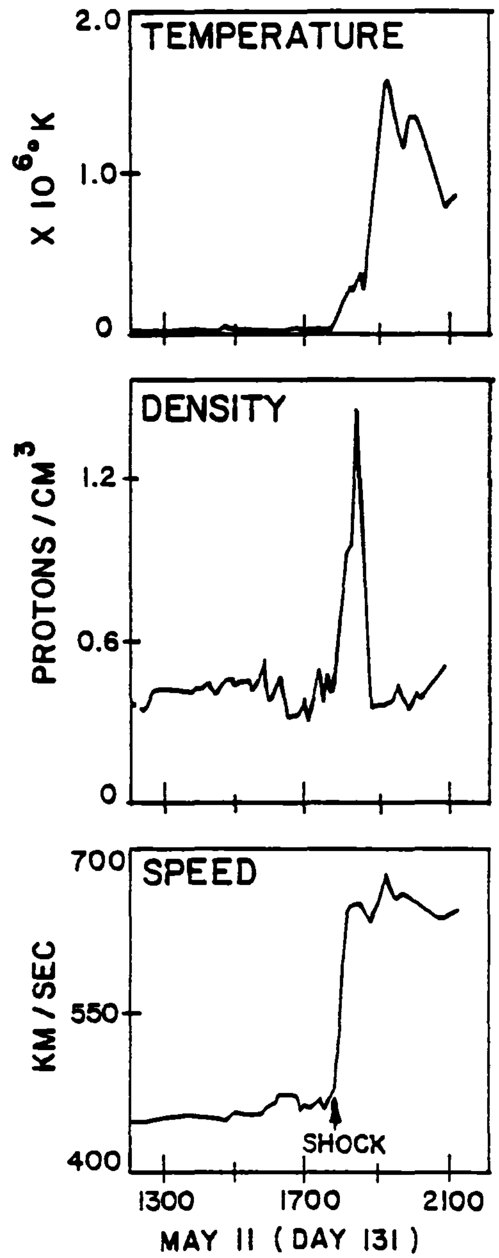

TEMPERATURE
25
12.5
0
X 10^3 °K
DENSITY
25
12.5
0
X 10^-2 PROTONS / CM^3
SPEED
460
445
430
KM / SEC
SHOCK
0300
0500
0700
0900
MAY 8 (DAY 128)

FIGURE 6



TEMPERATURE
X 10⁶ °K
2.0
1.0
0
DENSITY
PROTONS / CM³
1.2
0.6
0
SPEED
KM / SEC
700
550
400
SHOCK
1300
1700
2100
MAY 11 (DAY 131)

FIGURE 7

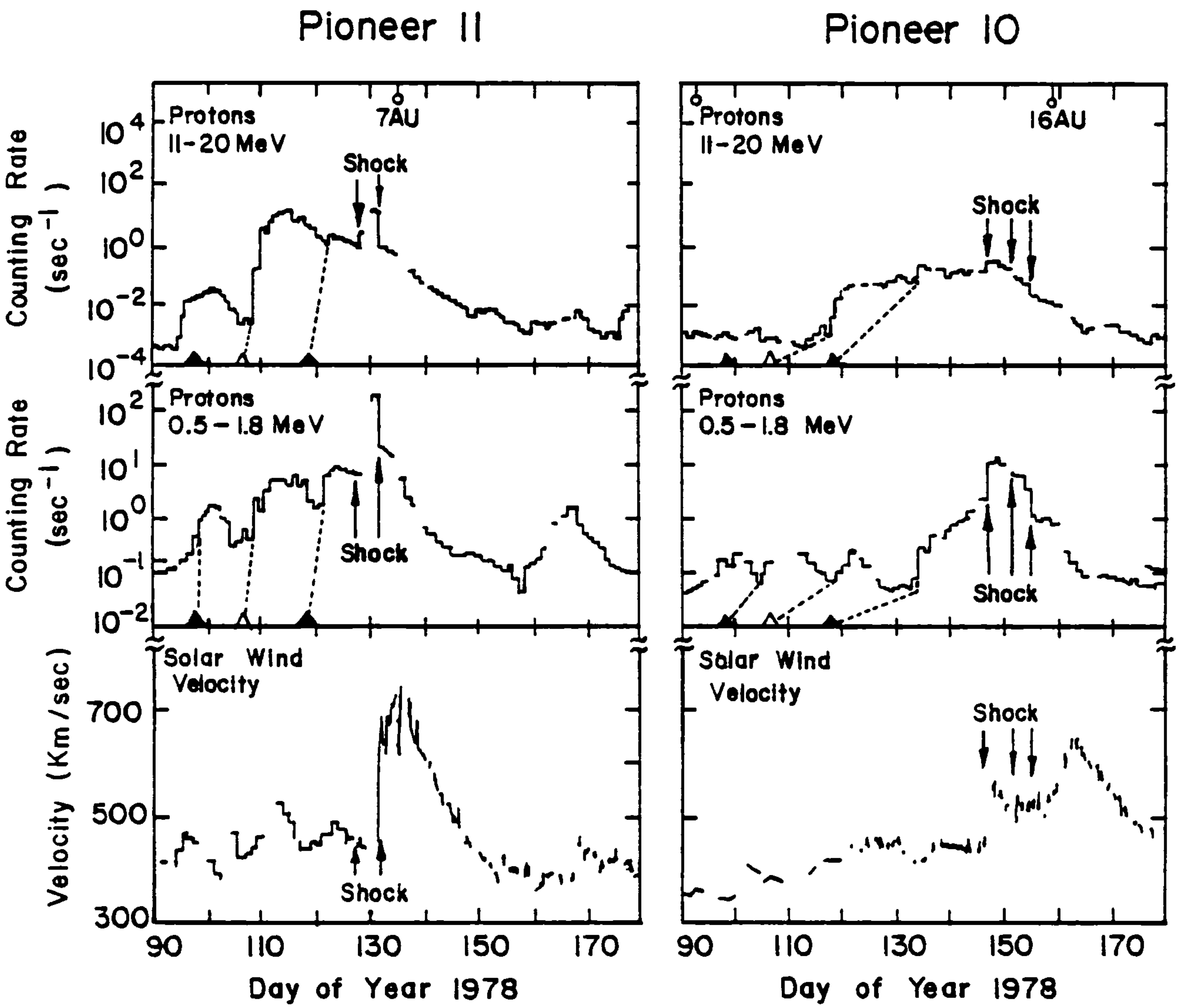

Pioneer II
Pioneer IO
Protons
II-20 MeV
7AU
16AU
Shock
Counting Rate (sec⁻¹)
Protons
0.5 - 1.8 MeV
Solar Wind
Velocity
Velocity (Km/sec)
Day of Year 1978

FIGURE 8

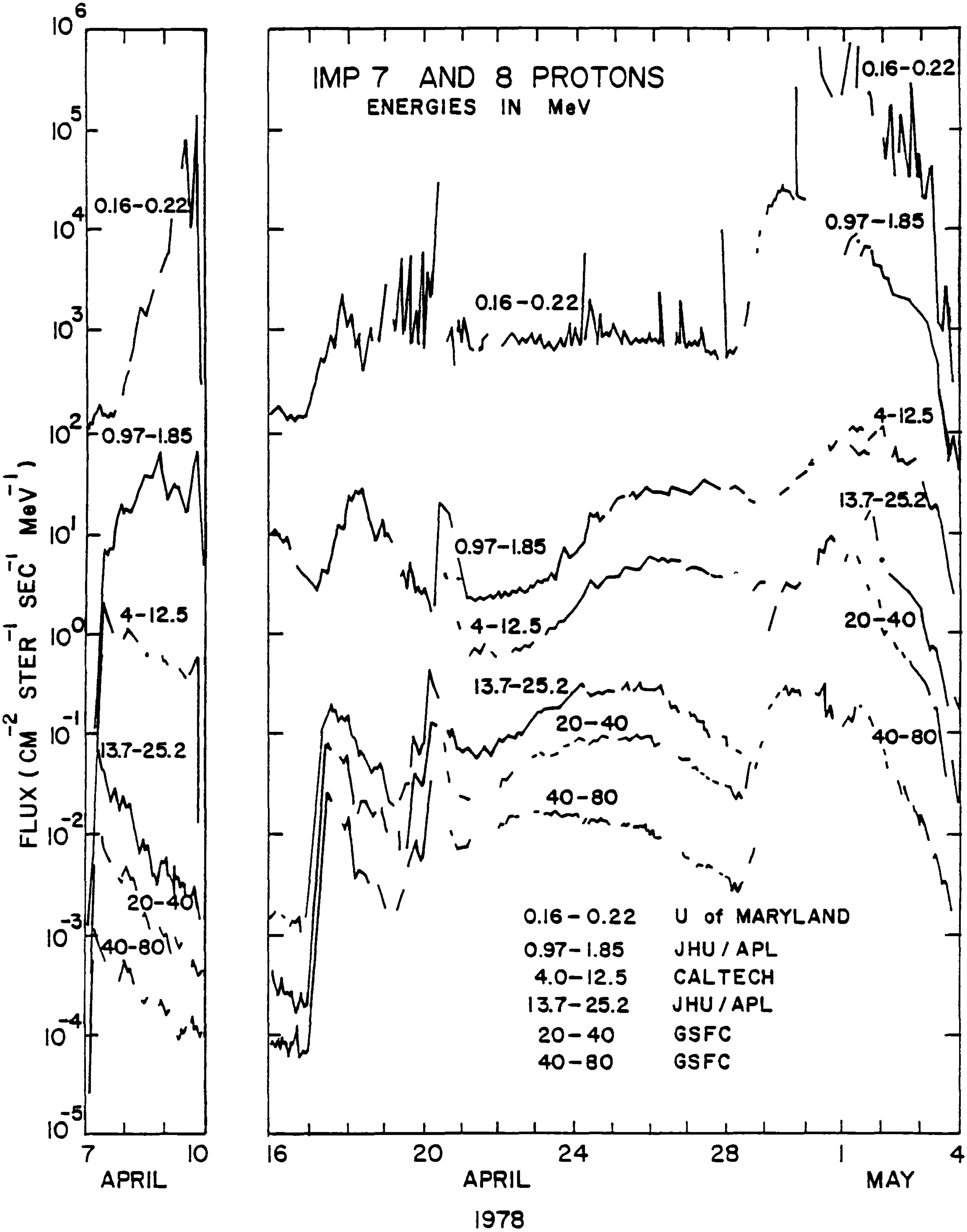

IMP 7 AND 8 PROTONS
ENERGIES IN MeV
FLUX (CM^{-2} STER^{-1} SEC^{-1} MeV^{-1})
0.16-0.22
0.97-1.85
4-12.5
13.7-25.2
20-40
40-80
0.16 - 0.22 U of MARYLAND
0.97 - 1.85 JHU / APL
4.0 - 12.5 CALTECH
13.7 - 25.2 JHU / APL
20 - 40 GSFC
40 - 80 GSFC
7
10
APRIL
16
20
24
28
1
4
APRIL
MAY
1978

FIGURE 9

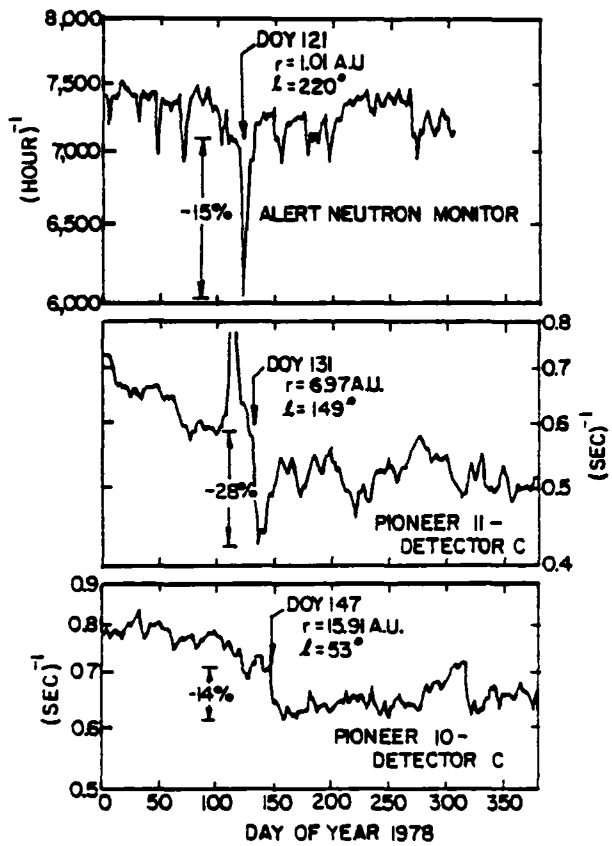
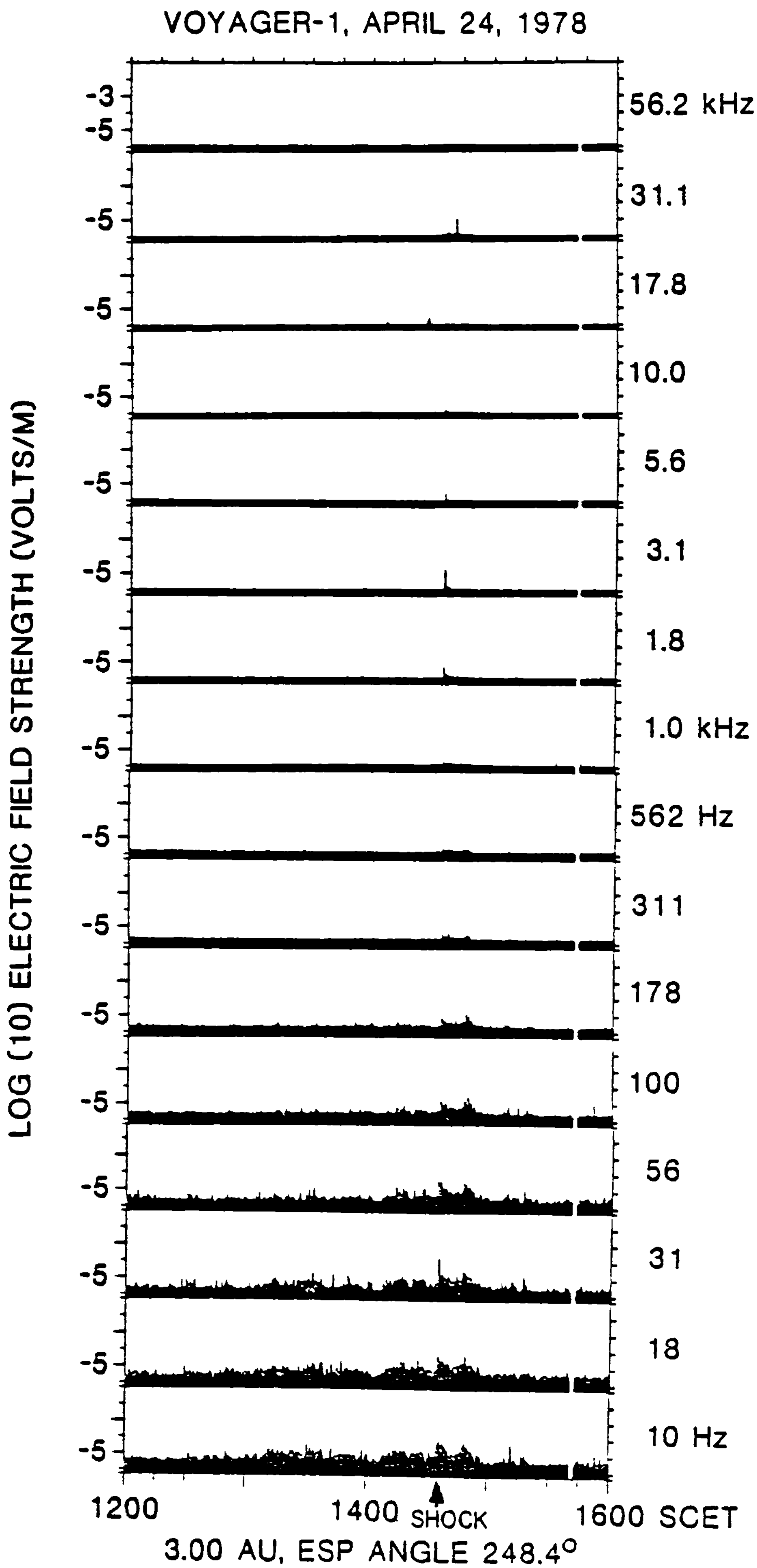

8,000
7,500
7,000
6,500
6,000
(HOUR)$^{-1}$
DOY 121
r = 1.01 A.U
ℓ = 220°
-15%
ALERT NEUTRON MONITOR
0.8
0.7
0.6
0.5
0.4
(SEC)$^{-1}$
DOY 131
r = 6.97 A.U.
ℓ = 149°
-28%
PIONEER 11 -
DETECTOR C
0.9
0.8
0.7
0.6
0.5
(SEC)$^{-1}$
DOY 147
r = 15.91 A.U.
ℓ = 53°
-14%
PIONEER 10 -
DETECTOR C
0
50
100
150
200
250
300
350
DAY OF YEAR 1978

FIGURE 10


VOYAGER-1, APRIL 24, 1978
LOG (10) ELECTRIC FIELD STRENGTH (VOLTS/M)
-3
-5
56.2 kHz
31.1
17.8
10.0
5.6
3.1
1.8
1.0 kHz
562 Hz
311
178
100
56
31
18
10 Hz
1200
1400
SHOCK
1600 SCET
3.00 AU, ESP ANGLE 248.4°
FIGURE 11

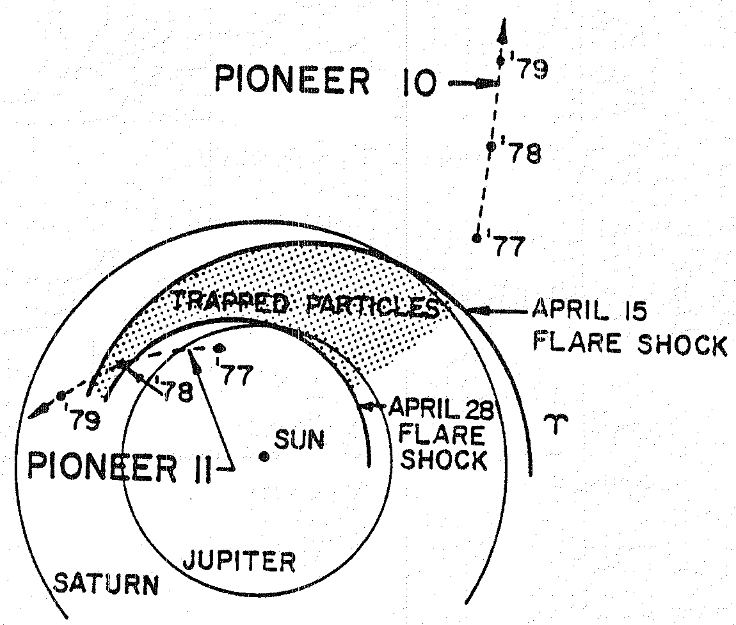
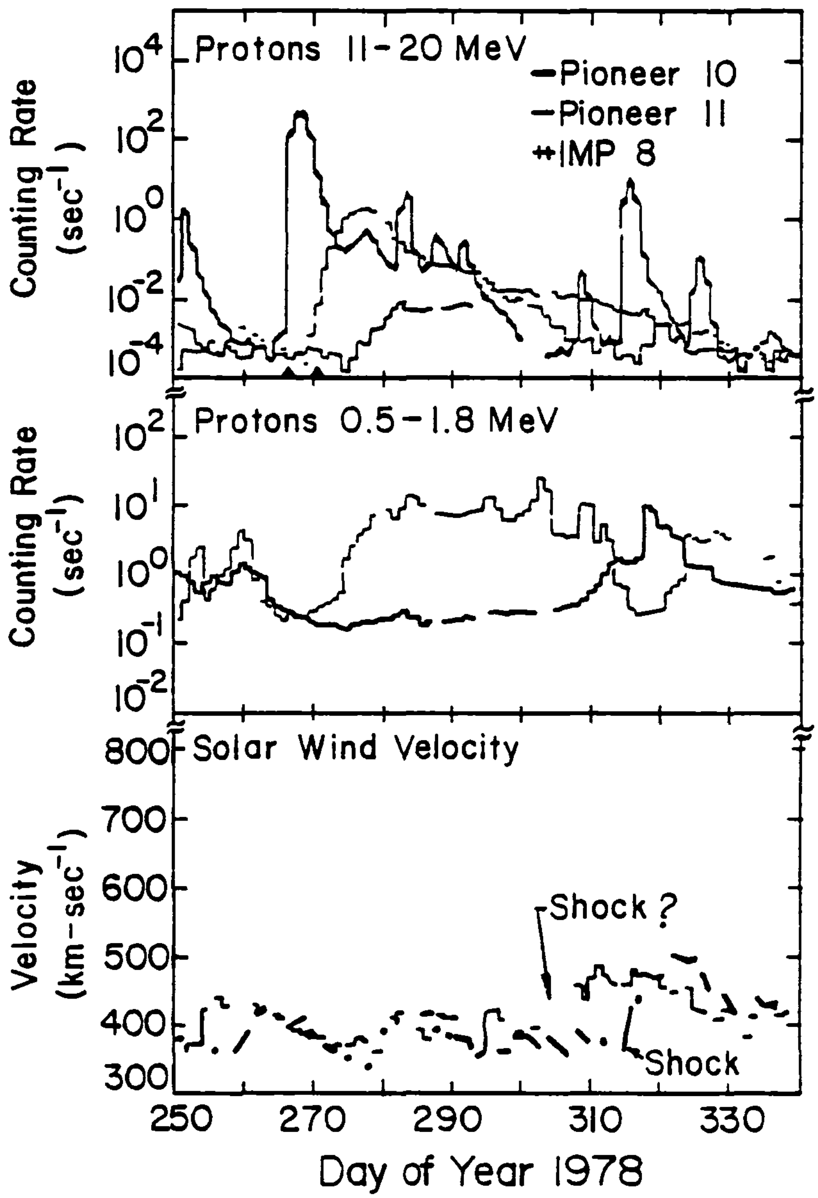

PIONEER 10
'79
'78
'77
TRAPPED PARTICLES
APRIL 15
FLARE SHOCK
'77
'78
'79
APRIL 28
FLARE
SHOCK
SUN
PIONEER 11
JUPITER
SATURN

FIGURE 12



Protons 11-20 MeV
Pioneer 10
Pioneer 11
IMP 8
Counting Rate (sec^{-1})
10^4
10^2
10^0
10^{-2}
10^{-4}
Protons 0.5-1.8 MeV
10^2
10^1
10^0
10^{-1}
10^{-2}
Solar Wind Velocity
Velocity (km-sec^{-1})
800
700
600
500
400
300
Shock ?
Shock
250
270
290
310
330
Day of Year 1978

FIGURE 13

APPENDIX III

BIOGRAPHICAL SKETCH

Devrie S. Intriligator

EDUCATION:

University of California, Los Angeles: Ph.D. Planetary and Space Physics (3/67)

Participant: Summer Faculty Institute in Space Physics, Columbia University and Goddard Institute for Space Studies, New York City (summer 1966)

Massachusetts Institute of Technology, Cambridge, Massachusetts: S.M. Physics (2/64)
S.B. Physics (6/62)

AWARDS AND PRIZES:

Recipient, NASA Public Service Group Achievement Award for participation in the plasma analyzer experiment on Pioneer 10 and Jupiter, 1974.

National Academy of Sciences, National Research Council Post-doctoral Fellowship, 1967-1968, 1968-1969.

Sigma Pi Sigma, Physics Honor Society, elected 1964.

Karl Taylor Compton Prize, M.I.T., May 1962.

PROFESSIONAL EXPERIENCE:

1979 -

Senior Research Physicist
Carmel Research Center
Post Office Box 1732
Santa Monica, CA 90406

Also affiliated with Earth and Space Sciences Institute
University of Southern California
171 SHS
University Park
Los Angeles, CA 90007

Research in experimental physics, space physics, plasma physics, and planetary physics.

Investigator of the solar wind ion analyzer on the International Solar Polar Mission, 1979-1980.

Co-Investigator of the plasma analyzer experiment on the Pioneer Venus Orbiter Mission, 1974- .

Co-Investigator of the plasma analyzer experiment on the Pioneer 10 Mission to Jupiter, 1968- .

Co-Investigator of the plasma analyzer experiment on the Pioneer 11 Mission to Jupiter and Saturn, 1968- .

Consultant to National Aeronautics and Space Administration, 1979, 1980, 1981.

Consultant to National Science Foundation, 1979- .

Consultant to Jet Propulsion Laboratory, 1980- .

Co-Chairman, National Academy of Sciences Study, "Solar Terrestrial Research for the 1980's," 1979, 1980, 1981.

Member, Advisory Committee, National Science Foundation, Division of Atmospheric Sciences, 1979, 1980, 1981.

Member, Atmospheric and Space Physics Management Operations Working Group, National Aeronautics and Space Administration, 1980- .

Principal Investigator of the proposed plasma investigation for the OPEN Mission, 1980- .

Principal Investigator of the proposed plasma investigation of the COMET Mission, 1980- .

Co-Investigator of the Pioneer 6, 7, 8, and 9 Ames Research Center solar wind plasma spectrometers, 1967- .

Principal Investigator of the USC Astrophysical Laboratory, a large (20 ft x 15 ft) experimental flowing plasma facility utilizing a 1 keV source, 1975- .

1972-1980	Member of the Faculty Department of Physics University of Southern California Los Angeles, CA 90007

Research and teaching in experimental physics, astrophysics, plasma physics, planetary physics, and space physics.

Co-Investigator of the plasma analyzer experiment on the Pioneer Venus Orbiter Mission, 1974- .

Co-Investigator of the plasma analyzer experiment on the Pioneer 10 Mission to Jupiter, 1968- .

Co-Investigator of the plasma analyzer experiment on the Pioneer 11 Mission to Jupiter and Saturn, 1968- .

Co-Chairman, National Academy of Sciences Study, "Solar Terrestrial Research for the 1980's."

Member, Advisory Committee, National Science Foundation, Division of Atmospheric Sciences, 1979-1980, 1980-1982.

Member, Committee on Solar-Terrestrial Research, Geophysics Research Board, National Academy of Sciences, National Research Council, 1976-1979.

Participant, National Academy of Sciences summer study on "Priorities in Upper Atmospheric Research for the 1980's," Woods Hole, Mass., July 2-9, 1978.

Principal Investigator of the proposed plasma investigation for the 1981-1982 Jupiter Orbiter (Galileo).

Co-Investigator of the Pioneer 6, 7, 8 and 9 Ames Research Center solar wind plasma spectrometers.

Principal Investigator of the USC Astrophysical Plasma Laboratory, a large (20 ft x 15 ft) experimental flowing plasma facility currently in operation with a 1 keV plasma source.

Nominated for Secretary, Solar-Planetary Relationships, American Geophysical Union 1978, 1979.

Member, Working Group 2, Panel B on the Interplanetary Medium and Its Interactions, Committee on Space Research (COSPAR), 1976-1979.

Principal Investigator of the proposed planetary and interplanetary plasma experiment on the Mariner Jupiter-Uranus Mission.

Principal Investigator of the proposed plasma interactions with the moon experiment on the Lunar Polar Orbiter Mission.

Co-Investigator of the proposed Ames Research Center solar wind plasma analyzer on the Mariner Jupiter-Saturn Mission.

Principal Investigator of the proposed Out-of-the-Ecliptic Explorer Mission.

Visiting Associate in Physics, California Institute of Technology, Pasadena, California, 1972-1973.

Guest Investigator for MSFC/AC Experiment on Apollo Telescope Mount on Skylabs 1, 2, and 3.

Member, Space and Atmospheric Physics Technical Committee, American Institute of Aeronautics and Astronautics, 1971, 1972, 1973.

Chairman, Space Science Award Selection Committee, American Institute of Aeronautics and Astronautics, 1973.

Member, Technical Committee, "The Exploration of the Outer Solar System," Joint AIAA-AGU Meeting, Denver, Colorado, July, 1973.

Taught Physics 100, a course for nonphysics majors, 1976-1977, 1977-1978, 1978-1979 and Physics 151, a course for physics majors, 1972-1973, 1974-1975, 1975-1876.

Supervisor of research of graduate students. Employer of graduate and undergraduate students assisting in various research projects.

Principal Investigator of research grants and contracts.

9/69 to Fall 1972: Research Fellow in Physics
California Institute of Technology
Pasadena, California 91125

Research and teaching in space physics, astrophysics, and plasma physics.

Member, Outer Planet Missions Plasma Team to place plasma experiments on missions to investigate extended regions of the solar system and the interstellar medium.

Co-Investigator of the Pioneer 6, 7, 8 and 9 Ames Research Center solar wind plasma probes.

Co-Investigator of the plasma analyzers on the Pioneer 10 and G missions to Jupiter in 1972 and 1973.

Taught Physics 224C, "Topics in Space Physics," a graduate student course, Spring 1970.

Taught Physics 93B, "Introduction to Space Physics and Astrophysics," a course for physics seniors, Winter 1971.

Taught Applied Physics 156, "Plasma Physics," a course for seniors and graduate students, 1971-1972.

Supervisor of research of one graduate student.

Employer of 10 undergraduate students assisting on various research projects.

Principal Investigator and Co-Investigator of research contracts and grants.

Awarded a President's Fund Grant.

Reviewer of papers for professional journals.

10/67 to 9/69: National Academy of Sciences Resident Research Associate
Space Sciences Division
NASA Ames Research Center
Moffett Field, California 94035

Research on the solar wind and cosmic rays.

Co-Investigator of the Pioneer 6, 7, 8, 9 and 10 Ames Research Center solar wind plasma spectrometers.

Co-Investigator on the plasma analyzer experiment on the Pioneer 10 and 11 missions to Jupiter.

Principal Investigator of the positive ion probe on the UCLA Small Scientific Satellite (S^3-C).

4/67 to 10/67: Assistant Research Geophysicist
Institute of Geophysics and Planetary Physics
University of California
Los Angeles, California 90024

Research on the sun, solar wind, and cosmic rays.

9/63 to 4/67: Research Assistant
Institute of Geophysics and Planetary Physics
University of California
Los Angeles, California 90024

Research on cosmic rays, astrophysics, geophysics, and planetary physics.

Principal Investigator on cosmic ray neutron balloon flights.

7/62 to 9/63: Physicist, Cosmic Ray Branch
Air Force Cambridge Research Laboratories
Bedford, Massachusetts

Research on cosmic rays and radiation belts.

Principal Investigator on numerous cosmic ray neutron balloon flights.

9/62 to 2/63: Grader, Physics Department
Massachusetts Institute of Technology
Cambridge, Massachusetts

Responsible for all grading and problem solving in graduate course on elementary particle physics.

10/61 to 7/62: Research Assistant, Cosmic Ray Group
Physics Department
Massachusetts Institute of Technology
Cambridge, Massachusetts.

Experimental and theoretical work on cosmic rays and space physics.

Co-Investigator on cosmic ray neutron balloon experiments.

6/61 to 10/61: Consultant Physicist
Institute de Fisica dell' Universita
Milan, Italy

Experimental work on cosmic rays and astrophysics.

Co-Investigator on cosmic ray balloon experiments.

1/60 to 6/61: Research Assistant, Cosmic Ray Group
Physics Department
Massachusetts Institute of Technology
Cambridge, Massachusetts

Experimental work on cosmic rays and space physics.

Participated on Explorer X solar wind plasma probe.

MAJOR PRESENTATIONS:

An International Conference on the Venus Environment, Palo Alto, California, November 1981. Paper, "The Venus Wake: Analysis and Implications of Pioneer Venus and Venera Plasma Observations."

International Association of Geodesy and Aeronomy, Edinburgh, Scotland, August 1981. Invited Paper, "Pioneer Observations of the Large-Scale Structure and Evolution of the Solar Wind."

XVII General Assembly of International Union of Geodesy and Geophysics, Canberra, Australia, December 1979. Invited paper, "Initial In Situ Plasma Analyzer Observations in the Vicinity of Saturn from Pioneer 11 Flyby."

International Association of Geodesy and Aeronomy, Canberra, Australia, December 1979. Invited paper, "Multipoint Studies of Evolving Solar Wind Structures Between 0.8 AU and 20 AU."

COSPAR and IAU Workshop on Solar Radio Astronomy, Interplanetary Scintillations and Coordination with Spacecraft, Culgoora, Australia, November 1979. Invited paper, "In-Situ Observations of Interplanetary Disturbances."

International Astronomical Union Sixteenth General Assembly, Montreal, Canada, August 1979. Invited paper, "The Distant Solar Wind."

International Astronomical Union Sixteenth General Assembly, Montreal, Canada, August 1979. Invited paper, "Travelling Interplanetary Phenomena and the Solar Maximum Year."

IAU Symposium No. 91 on Solar and Interplanetary Dynamics, Cambridge, Massachusetts, August 1979. Invited paper, "Transient Phenomena Originating at the Sun - An Interplanetary View."

Second International Colloquium on Mars, Pasadena, California, January 1979. Invited paper, "Mars in the Solar Wind: Implications of a Venus-like Interaction."

Solar Wind 4 Conference, Burghausen, Federal Republic of Germany, August 1978. Invited paper, "Solar Wind Fluctuations."

Space Research Institute (IKI), USSR Academy of Sciences, Moscow, USSR, June 1978. Invited lecture, "In-Situ Observations of the Radial Gradient in the Solar Wind."

SIZIRAN, USSR Academy of Sciences, Irkutsk, USSR, June 1978. Invited lecture, "Direct Observations of the Solar Wind at Extended Heliocentric Distances."

Nuclear Science Institute, Moscow University, USSR Academy of Sciences, Moscow, USSR, June 1978. Invited lecture, "Pioneer 10 and 11 Observations of the Solar Wind Beyond 1 AU."

IZMIRAN, USSR Academy of Sciences, Moscow, USSR, June 1978. Invited lecture, "The Radial Evolution of the Solar Wind Beyond 1 AU."

Leendert Dirk de Feiter Memorial Symposium on the Study of Travelling Interplanetary Phenomena (STIP), Tel-Aviv, Israel, June 1977. Invited paper "Evolution of Streams and Shocks in the Solar Wind."

14th International Cosmic Ray Conference, Munich, West Germany, August 1975. "The Solar Wind Between 0.7 AU and 5.0 AU."

14th International Cosmic Ray Conference, Munich, West Germany, August 1975. "Direct Observations of the Solar Wind Interaction With Jupiter."

14th International Cosmic Ray Conference, Munich, West Germany, August 1975. "The Solar Cycle Variation in the Solar Wind and the Modulation of Cosmic Rays."

14th International Cosmic Ray Conference, Munich, West Germany, August 1975. "Measurements of Large Scale Turbulence in the Solar System."

14th International Cosmic Ray Conference, Munich, West Germany, August 1975. "Solar Wind Observations Associated With the August 1972 Solar Events."

Neil Brice Memorial International Symposium on Magnetospheres of the Earth and Jupiter, Frascati, Italy, May 1974. Invited paper, "Pioneer 10 Observations of the Solar Wind and Its Interaction With Jupiter: Plasma Electron Results."

Neil Brice Memorial International Symposium on the Magnetospheres of the Earth and Jupiter, Frascati, Italy, May 1974. Invited paper, "Pioneer 10 Observations of the Jovian Magnetosphere: Plasma Electron Results."

55th Annual Meeting American Geophysical Union, Washington, D.C., April 1974. Invited paper, "Pioneer 10 Electron Encounter Results from the Ames Research Center Plasma Analyzer Experiment."

Solar Wind Conference, Asilomar, California, March 1974. "The Radial Gradient and the Role of Turbulence in the Solar System."

Solar Wind Conference, Asilomar, California, March 1974. "The Power Associated with Density Fluctuations and Velocity Fluctuations in the Solar Wind."

National Fall American Geophysical Union Meeting, San Francisco, December 1973. Invited paper, "Power Spectra of the Interplanetary Plasma Beyond 1 AU."

International Association of Geodesy and Aeronomy, Kyoto, Japan, September, 1973. Invited paper, "Solar Wind Parameters and Magnetospheric Activity."

International Union of Geodesy and Geophysics, Moscow, USSR, August 1971. Invited review paper, "A Review of Quantitative Studies to Predict the Solar Wind Interaction With the Geomagnetic Field."

Solar Wind Conference, Asilomar, California, March 1971. "Review of Preliminary Power Spectra of the Interplanetary Plasma Density."

Solar Wind Conference, Asilomar, California, March 1971. "Initial Power Spectra of the Solar Wind Velocity Components."

International Symposium on Solar Terrestrial Physics, Leningrad, USSR, May 1970. "Solar Wind Plasma Configurations and Their Relation to Solar, Interplanetary, and Magnetospheric Activity" (with John H. Wolfe) (abstract published in program book).

International Symposium on the Physics of the Magnetosphere, Washington, D.C., September 1968. "Simultaneous Plasma, Electric Field, and Magnetic Field Measurements in the Expected Region of the Extended Geomagnetic Tail at 500 RE" (with John H. Wolfe, D.D. McKibbin, F.L. Scarf, E.G. Greenstadt, N.F. Ness, and F. Mariani) (abstract published in program book).

Solar Terrestrial Relations, Sheffield, England, July 1968. "Preliminary Comparison of Solar Wind Plasma Observations in the Geomagnetospheric Wake at 1000 and 500 Earth Radii" (with J.H. Wolfe, D.D. McKibbin, H.R. Collard).

Panelist, Gordon Conference on the Physics of Space Plasmas, Tilton, New Hampshire, July 1968.

Numerous presentations at professional society meetings including those of the American Physical Society, the American Geophysical Union, and the American Astronomical Society (abstracts published in respective bulletins).

PUBLICATIONS*

Intriligator, D.S., and W.D. Miller, Plasma Shocks and Energetic Particles in the Outer Solar System: Trapping and Asymmetry - Observations from Pioneers 10 and 11, Journal of Geophysical Research, in press, 1982.

Intriligator, D.S., and G.R. Steele, Observations of Structuring in the Downstream Region of a Large Spherical Model in a Laboratory Simulated Solar Wind Plasma, Journal of Geophysical Research, in press, 1982.

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Perez-de-Tejada, H., D.S. Intriligator, and C.T. Russell, Non-Alignment of Planetary O^+ Fluxes and Magnetic Field Lines in the Venus Wake, Nature, submitted, 1981.

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16. Abstract

Two major achievements, each of which is unique, were accomplished under this contract. The first was the discovery that the Pioneer 10 plasma analyzer detected the Io plasma torus during the spacecraft's flyby of Jupiter in 1973. Evidence was found of corotating ions which appear to be primarily S^{++} and O^{++} in the Pioneer 10 plasma profile shows a relative variation with radial distance remarkably similar to the Voyager density profile. Both profiles show a well defined peak falling off steeply toward Jupiter and gradually decreasing away from Jupiter. The Pioneer 10 plasma data are also consistent with a constant temperature for at least 0.5 R_J outside Io's orbit. The second major achievement concerned the discovery that interplanetary solar wind plasma shocks can trap energetic particles (cosmic rays) for weeks and out to distances of 17 AU. We found that energetic particles (0.5 MeV to 20 MeV) were confined between two plasma shocks from solar flares (April 15 and 28, 1978) as the shocks propagated outward in the solar system. Shocks associated with both flarea are detectable in the Pioneer 10 and Pioneer 11 plasma analyzer data. The shock/flare associations are different from those previously published by others studying the interplanetary events. The apparent ability of a shock whose plasma signature is extremely weak to confine MeV protons in the outer solar system may have significant implications for cosmic ray studies.

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